Neutron Optics & Instrumentation

Bill Hamilton

Neutron Instrument & Source Division

Oak Ridge National Laboratory

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Chadwick identifies the neutron - 1932

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Letters to the Editor

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Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

...as appear to be abundant at Oldoway. Either the skeletons are all complete, as in the *Stenomylus* quarry at Sioux City, Nebraska, or are all scattered and ...

... found long ago, are entirely without satisfactory evidence as to their mode of occurrence.

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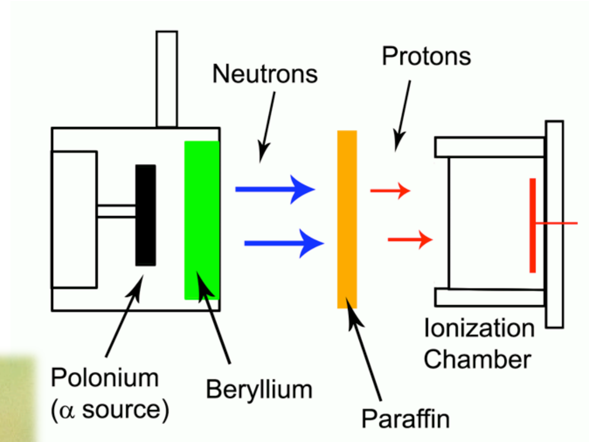
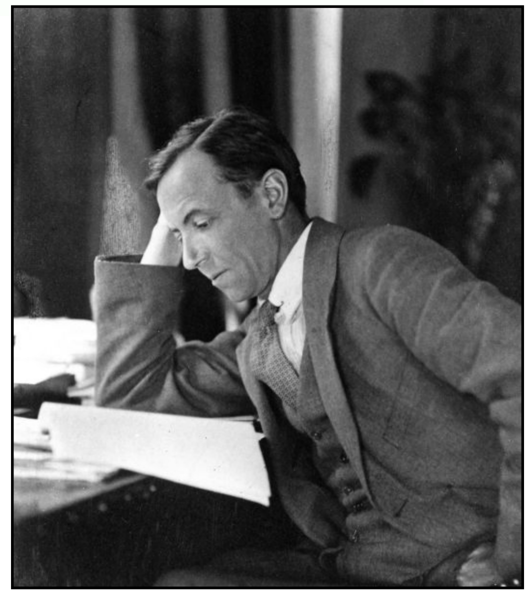




1935 Nobel Prize in Physics "for the discovery of the neutron"

Properties of the Neutron

Neutrons are **NEUTRAL** particles

They are highly penetrating:*

- **can be used as nondestructive probes**
- **can be used to study samples in severe environments**

Neutrons have a **MAGNETIC** moment

They can be used to:

- **study microscopic magnetic structure**
- **study magnetic fluctuations**
- **develop magnetic materials**

Neutrons have **SPIN**

They can be:

- **formed into polarized neutron beams**
- **used to study nuclear (atomic) orientation**
- **used for coherent and incoherent scattering.**

The **ENERGIES** of thermal neutrons are similar to the energies of elementary excitations in solids.

The **WAVELENGTHS** of neutrons are similar to the distance between atoms:

They can determine

- **atomic structure**
- **structural transitions**

Neutrons "see" **NUCLEI**

They are

- **sensitive to light atoms,**
- **can exploit isotopic substitution contrast variation to differentiate molecular (sub)structures.**

"highly penetrating" ⇔ weakly interacting …

(Thermal) Neutron Bragg Diffraction

An obvious consequence of things already well known in 1932:

X-ray diffraction (1912 the Braggs, father and son)

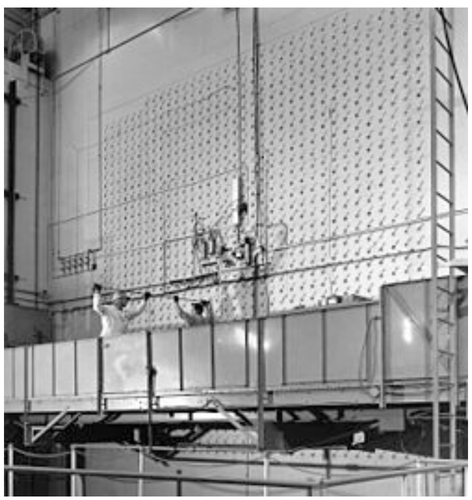
& de Broglie wavelength hypothesis confirmation (1927 Davisson & Germer)

& Chadwick's determination of the neutron mass (1.0067 m_p)

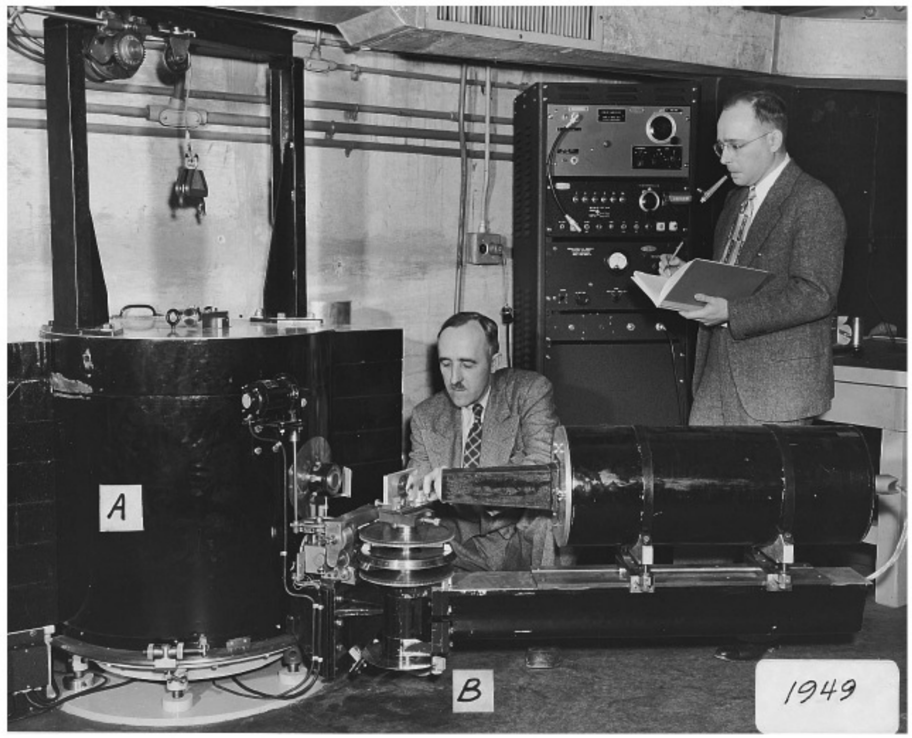
⇒ 1936 Mitchel & Powers and Halban & Preiswerk – Bragg diffraction demonstration

Early problems: source & interaction strengths, neutron energies & neutron detection & WWII …

X-10 Graphite reactor 1943 (Clinton Engineering works)



E.O. Wollan and C. G. Shull 1945/1946 …



XRD from UC 1948 after n mods

"Scientists at Oak Ridge were very anxious to find real honest-to-goodness scientific uses for the information and technology that had been developed during the war at Oak Ridge and at other places associated with the wartime Manhattan Project."

Clifford Shull speaking about arriving to work at "Clinton Laboratories" in 1946

What is a neutron scattering instrument ?

Neutron scattering measurements probe nuclear positions and motions in a sample from determinations of the wavevector change (**Q**) and the energy change (E) of the neutron - S(**Q**,E).

What do we need to accomplish this?

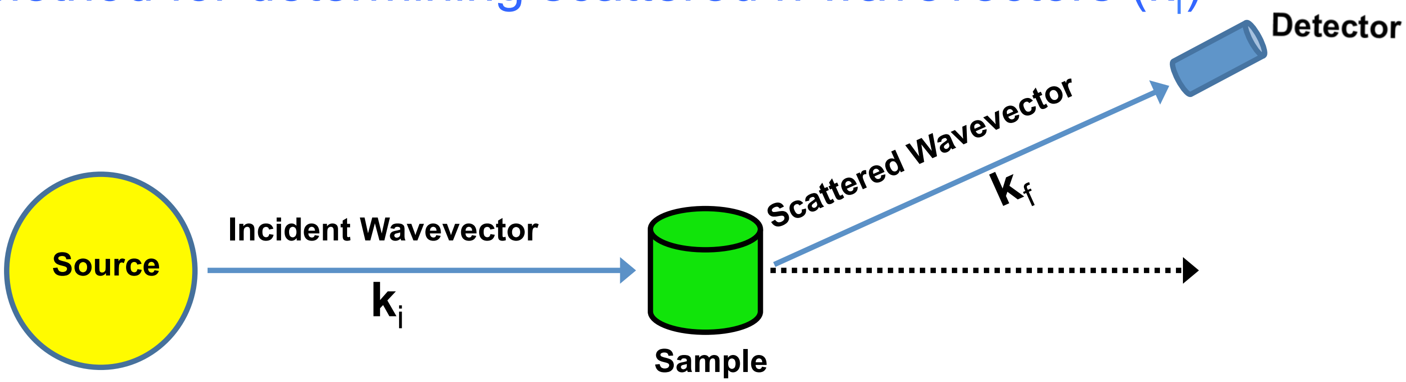
1. A source of neutrons
2. Selection of the wavevector of the incident neutrons (k_i)

3\. a) An interesting & otherwise intractable question (n/$/t low)

3\. b) A "large" sample (n interactions are generally "weak")

3\. c) An otherwise well characterized sample (n/$/t low)

4. A neutron detector – or lots of them (… n/$/t low)
5. A method for determining scattered n wavevectors (k_f)



Wave-particle duality machine

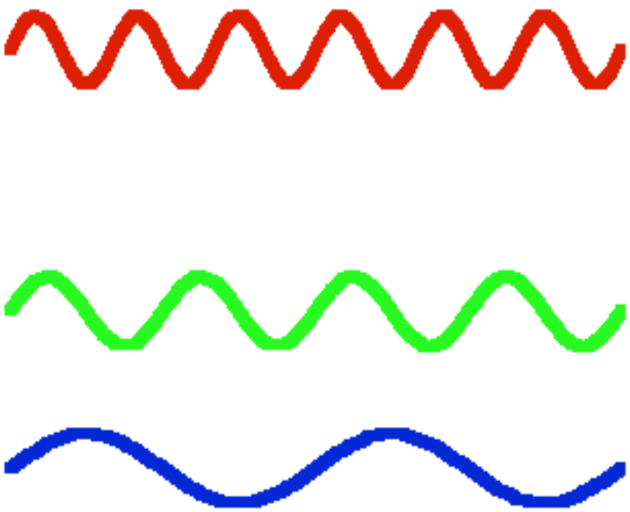
$$p = \frac{h}{\lambda}$$

de Broglie

$$\Downarrow$$

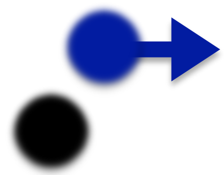
Sample interactions …

Instrumentally
Paths, flight timing,
collimation, detection …



$$\lambda_n = \frac{h}{p_n} = \frac{h}{m_n \mathrm{v}_n}$$

$$E_n = \frac{p_n^2}{2m_n} = \frac{h^2}{2m_n \lambda_n^2}$$



wave … mostly

particle … mostly

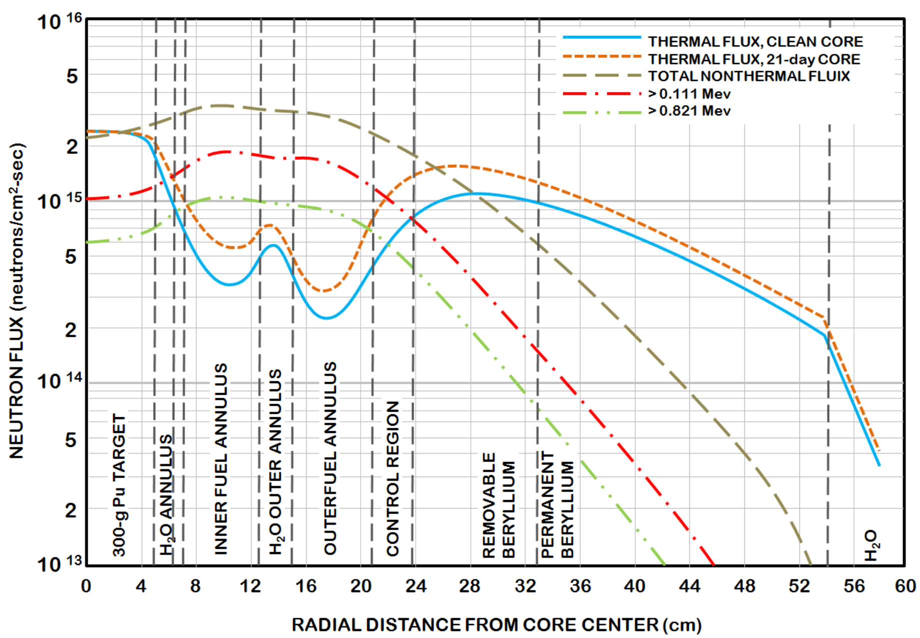
Nuclear Reactors – continuous

Neutrons produced by fission (usually ^{235}U)

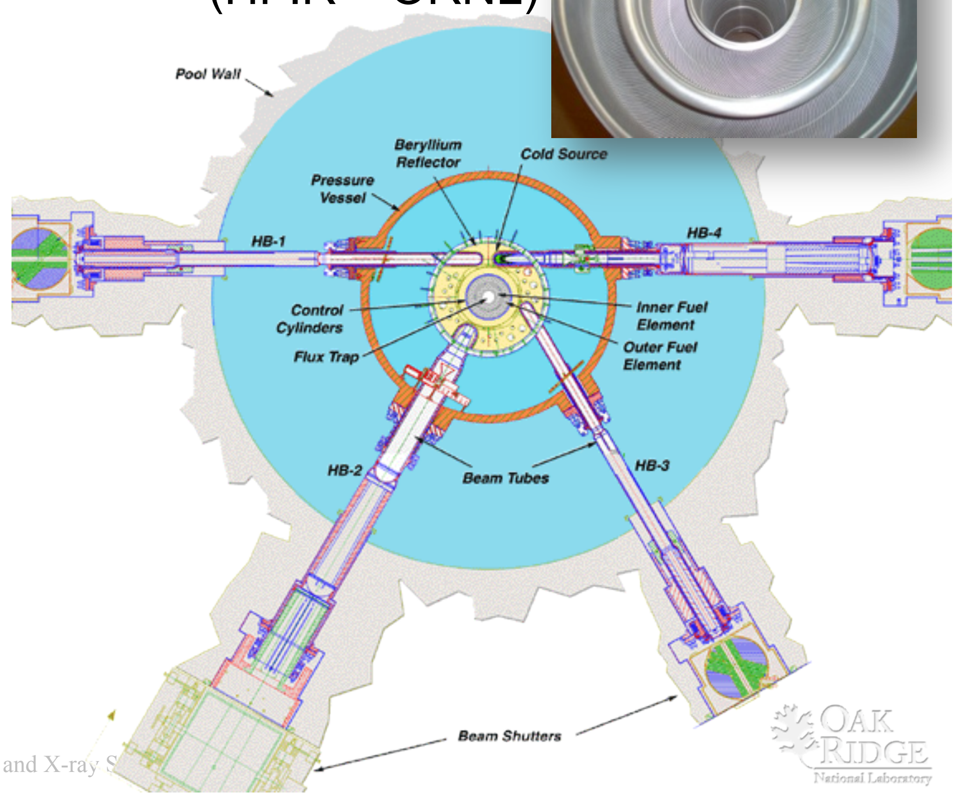
Fission requires moderation (~"thermal" neutrons)

Neutrons at a more or less constant rate

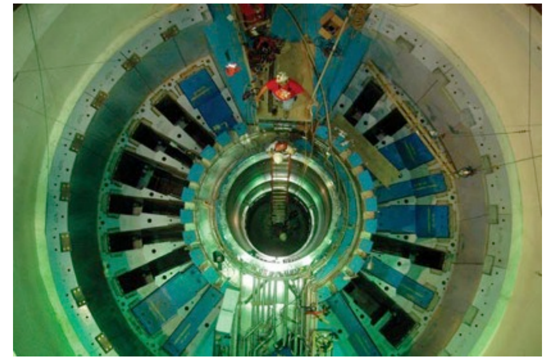
Very high neutron fluxes ~10^{15} n/cm^2/s



High Flux Isotope Reactor (HFIR – ORNL)



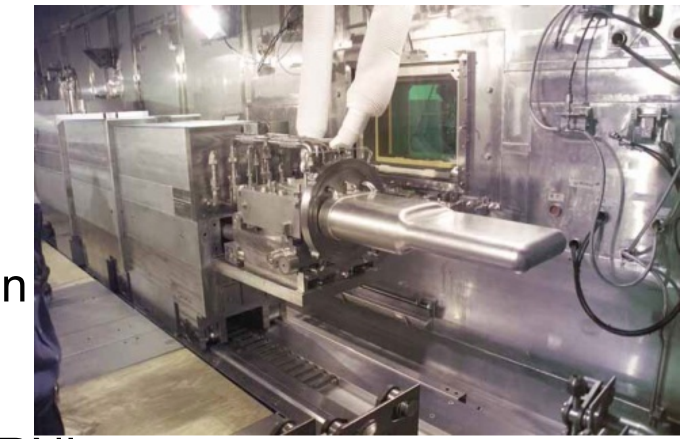
Spallation Sources – mostly pulsed



Neutrons produced by nuclear spallation

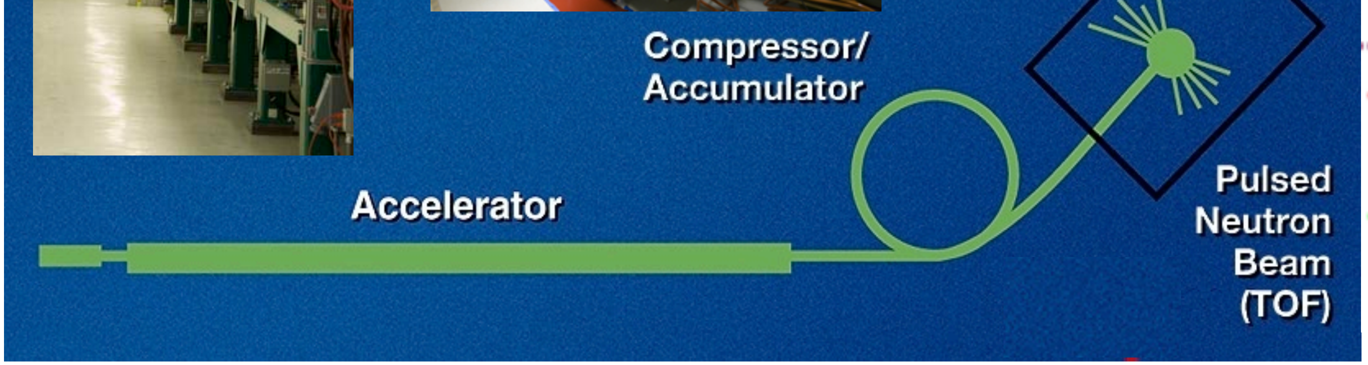
Accelerator beams usually pulsed => time structure

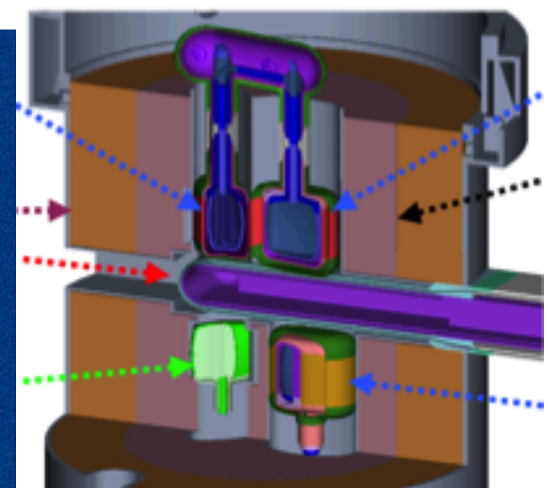
Neutron energies must be moderated (a lot)



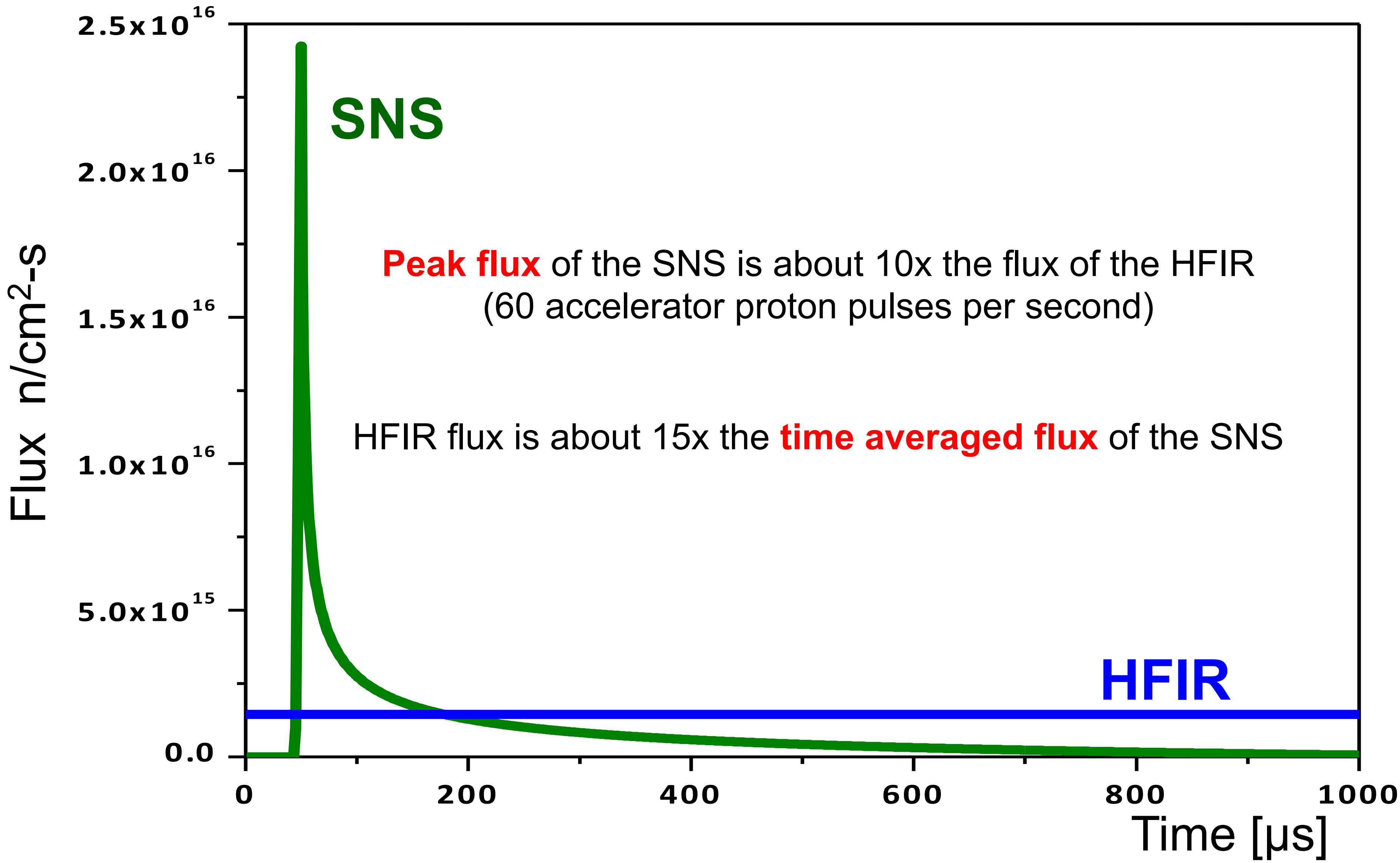
Extremely high peak fluxes ~10^{16} n/cm^2/s

Spallation
Neutron
Source
SNS - ORNL





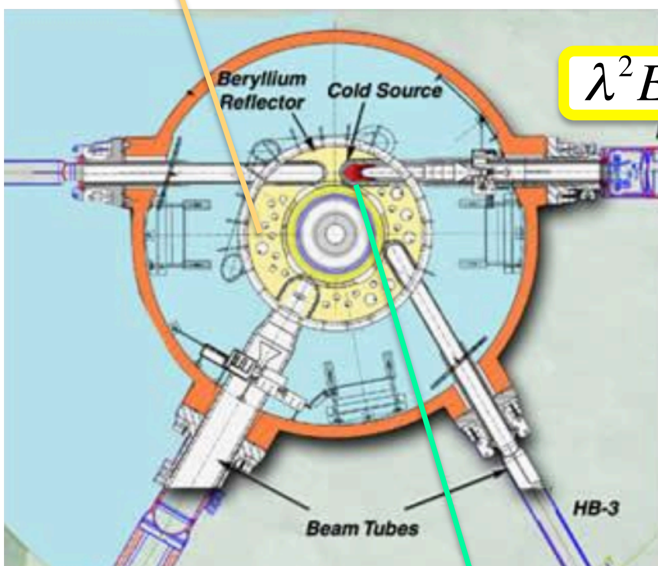
Primary characteristics of the sources



Neutron Moderation: GeV & MeV ➔ eV & meV

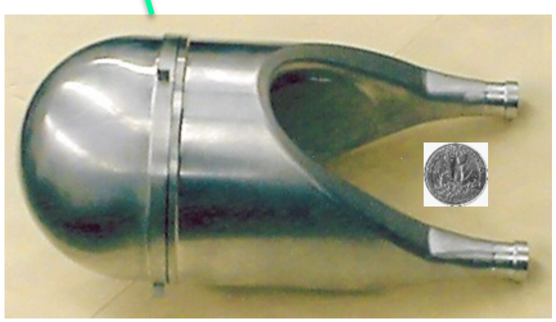
Neutrons bounce off something light (better energy transfer) maintained at a temperature consistent with the energy/wavelength desired

Most HFIR instruments beam tubes view water cooled Be reflector/moderator or LH_2 Cold Source (T~20K)



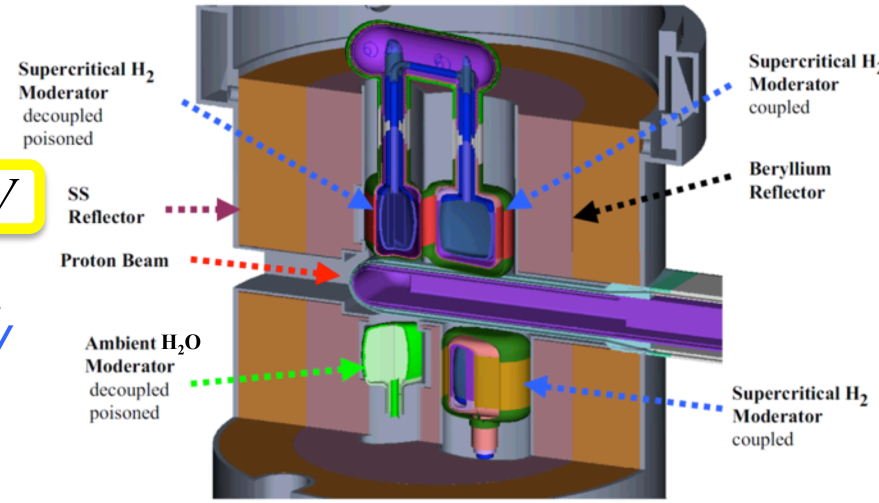
$$\lambda^2 E = 81.82\ \text{Å}^2 meV$$

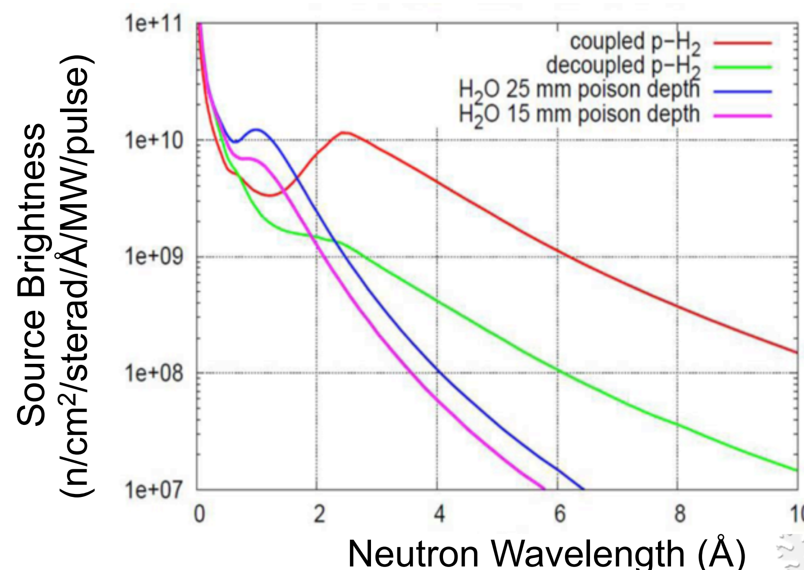
"Thermal" 2 Å
$k_B T$ ~ 25 meV
"Cold" 6 Å
$k_B T$ ~ 2 meV



HFIR Cold Source
lH_2 flow head vessel

SNS Moderators



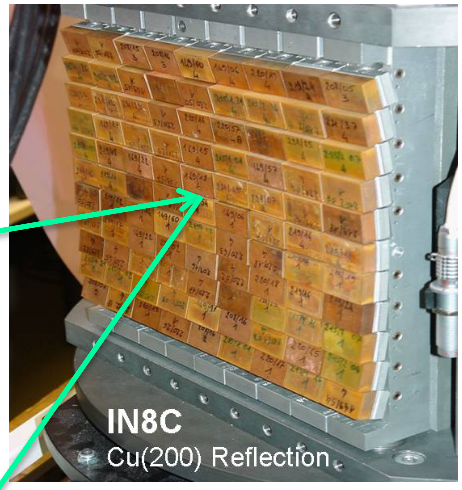


Determining the wavevectors: $\boldsymbol{k}_i$ & $\boldsymbol{k}_f$

Diffraction and selectors – Reactors mainly

Time-of-flight & Choppers – Pulsed sources mainly

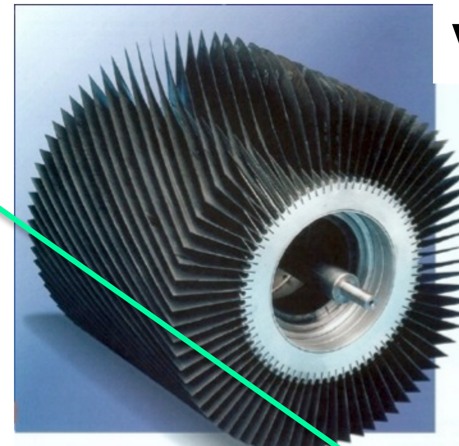
(Focusing) Cu(200) crystal monochromator ILL France



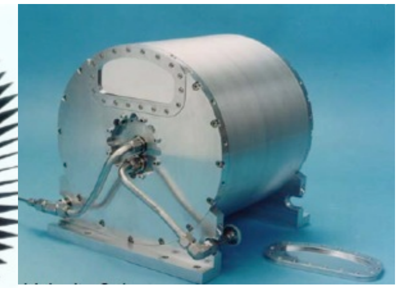
$$n\lambda = 2d\sin\theta$$

$$\lambda \sim 1..5\ \text{Å}$$

$$\Delta\lambda/\lambda \sim 1\%$$



Velocity Selector



Astrium GmbH

$$V_n \sim 1/\lambda \sim \text{fan pitch} * \text{speed}$$

$$\lambda \sim 4..20\ \text{Å} \quad \Delta\lambda/\lambda \sim 5..20\%$$

Time-of-flight

$$V_n = \frac{3956.034\,ms^{-1}}{\lambda[\text{Å}]}$$

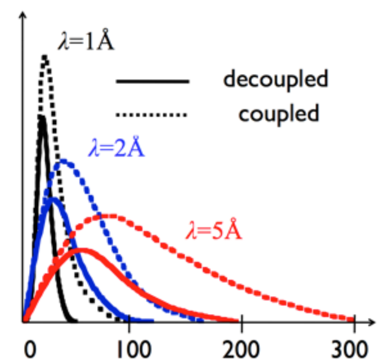
$$TOF[s] = \frac{D}{V_n} = \frac{D[m].\lambda[\text{Å}]}{3956.034\,ms^{-1}}$$

$$D = 10m,\ \lambda = 4\text{Å} \Rightarrow TOF = 0.010s = 10ms$$

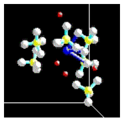
Time zero from pulse
TOF ~ 10 ms
ΔTOF ~ 100 μs
(moderator dependent)

$$\lambda \sim 0.5..20...\ \text{Å}$$

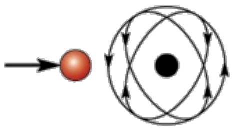
$$\Delta\lambda/\lambda \sim 1\%$$



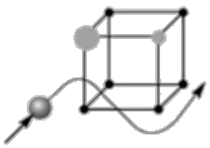
So, why neutrons ?



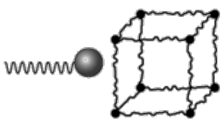
1. Neutrons (now) have the right wavelength



2. Neutrons see the Nuclei



3. Neutrons see light Atoms next to Heavy Ones



4. Neutrons measure the Velocity of Atoms

5. Neutrons penetrate deep into Matter

6. Neutrons see Elementary Magnets

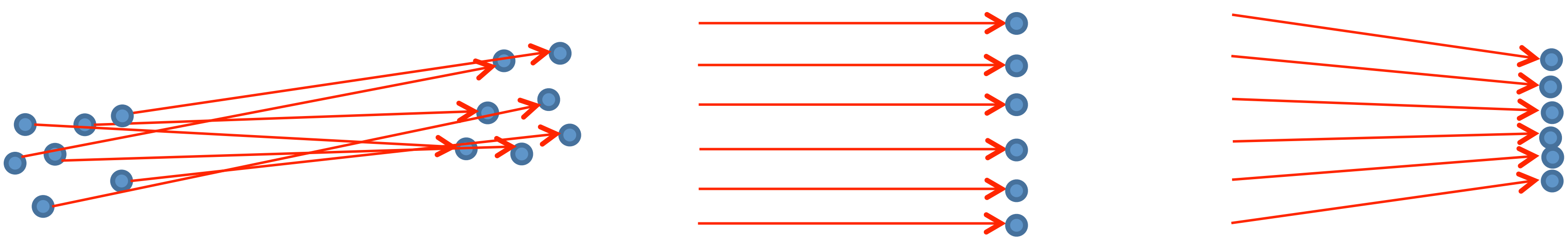
"Liouville's theorem" (Gibbs 1902)

" … the phase space density of non-interacting particles cannot be increased by conservative forces."

$$\frac{N_n}{\Delta k^3 \Delta r^3}$$

⇒ To increase intensity at a given (Q,E) we must increase the phase space volume

Simple Instrumental Implication:
It costs flux to increase resolution and it costs resolution to increase flux



~parallel
Small Δk^3 ⇔ high resolution
Need large sample V

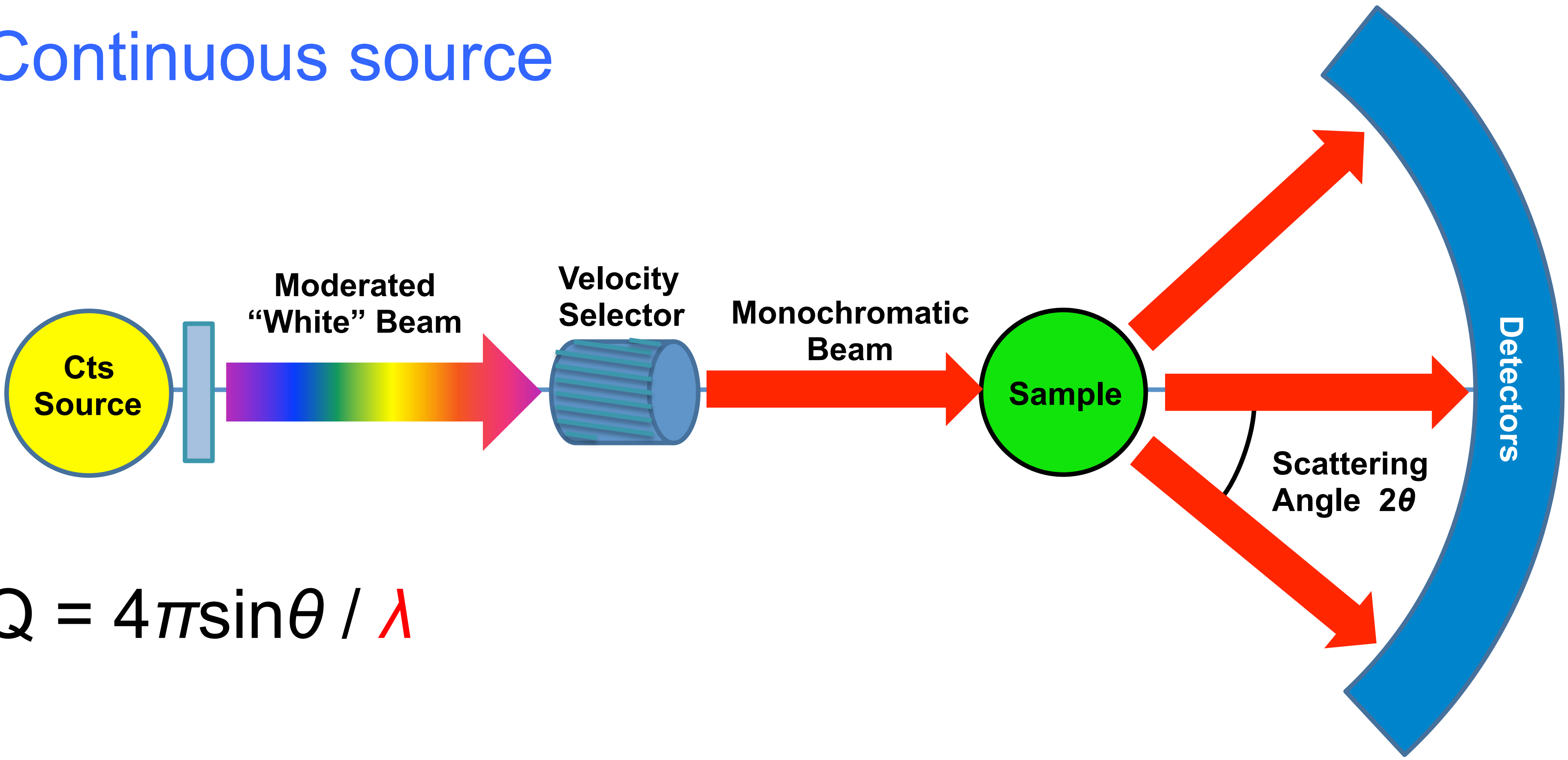
converging optics
smaller sample V
Larger Δk^3 ⇔ lower res.

Thermodynamic limit, so in those terms you tend to "lose" more than you "gain"
Drives the multiplicity of neutron instruments

http://en.wikipedia.org/wiki/Liouville's_theorem_(Hamiltonian)

Steady state use of the neutron spectrum (Elastic scattering example)

Continuous source



$$Q = 4\pi \sin\theta / \lambda$$

uses narrow spectral band

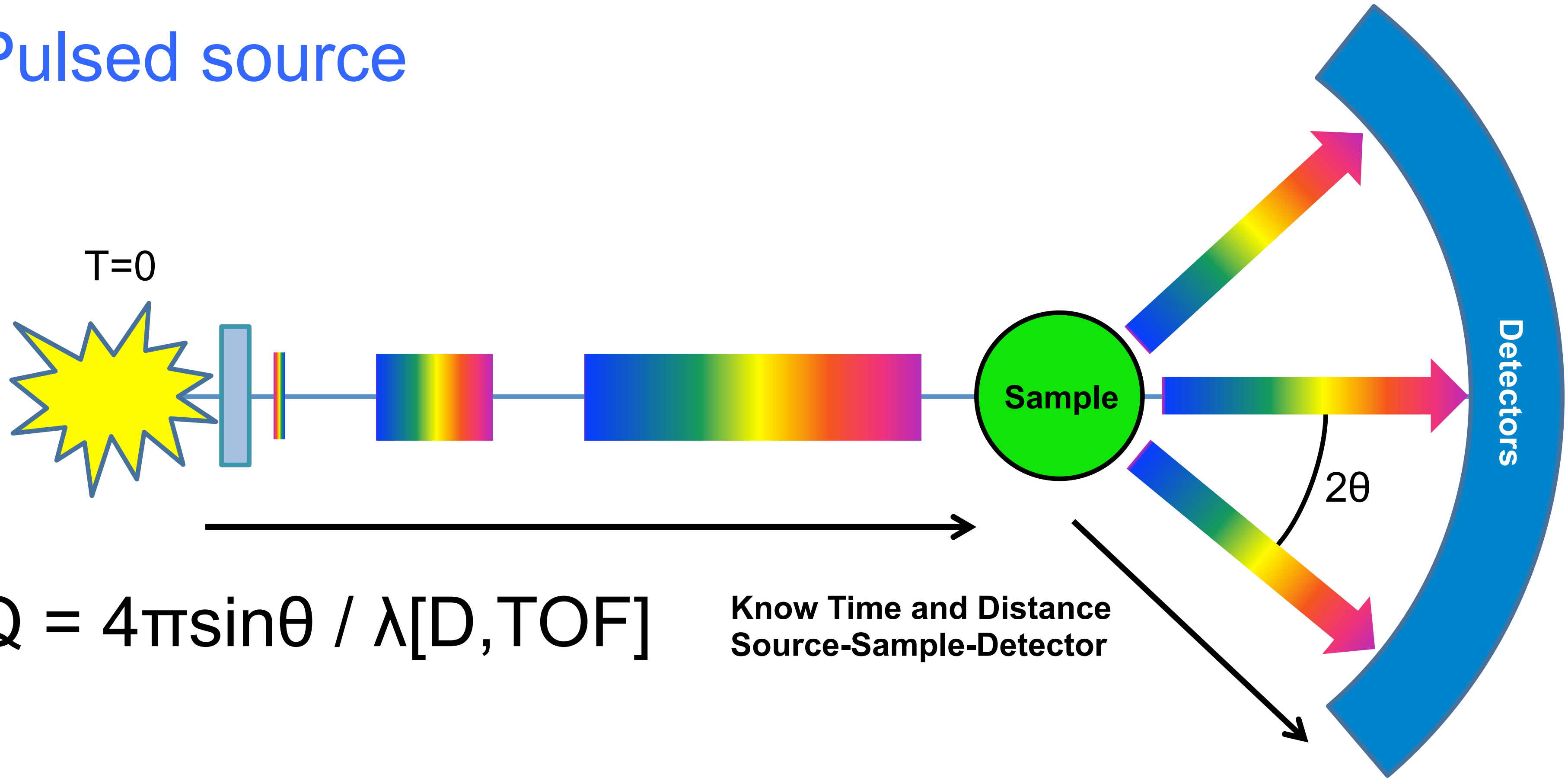
Steady state use of the neutron spectrum (Elastic scattering example)

NG7-SANS NIST Center for Neutron Research

uses narrow spectral band

TOF use of the neutron spectrum (Elastic scattering example)

Pulsed source

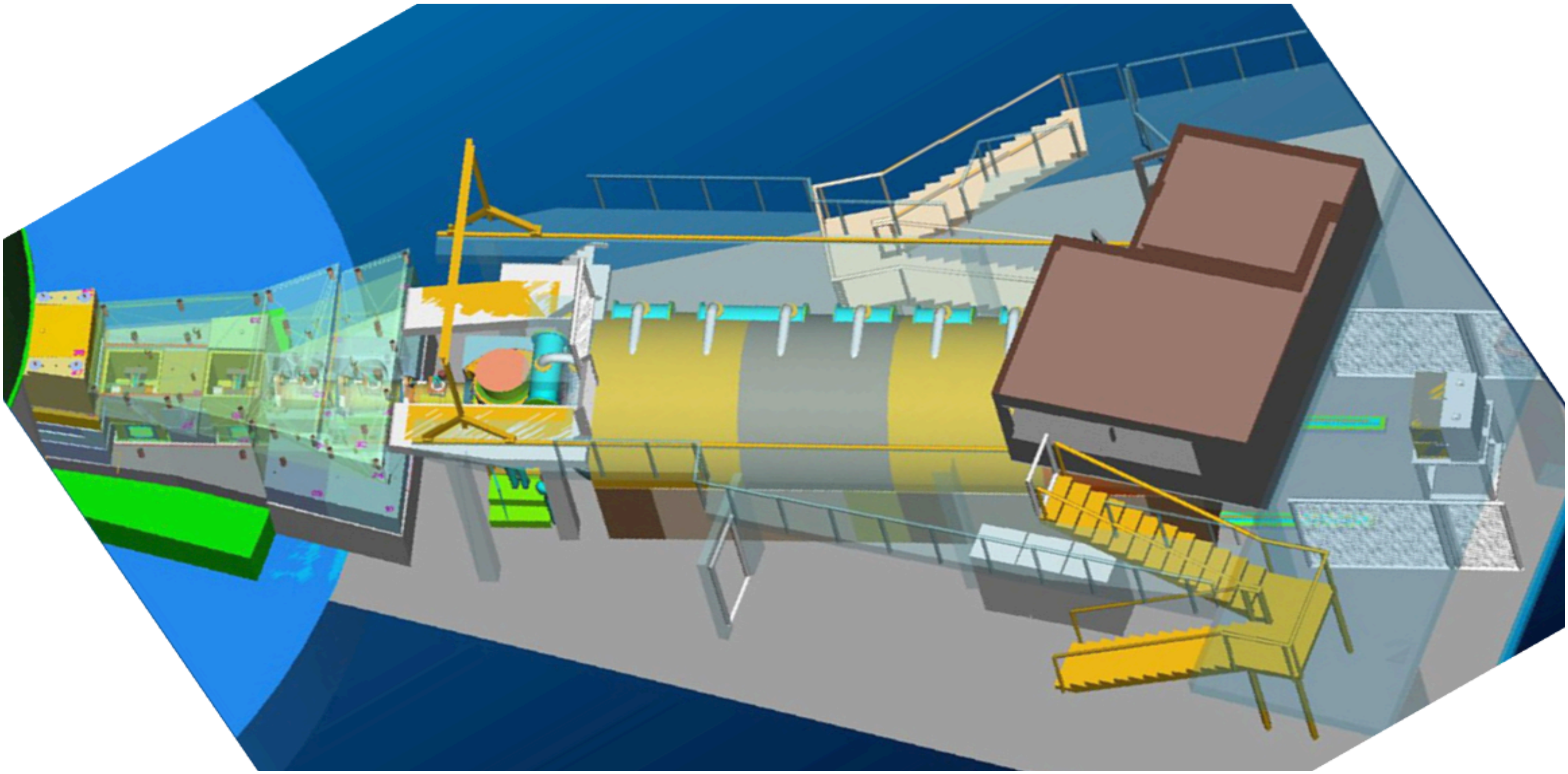


$$Q = 4\pi\sin\theta \,/\, \lambda[D,TOF]$$

uses a wide spectral band

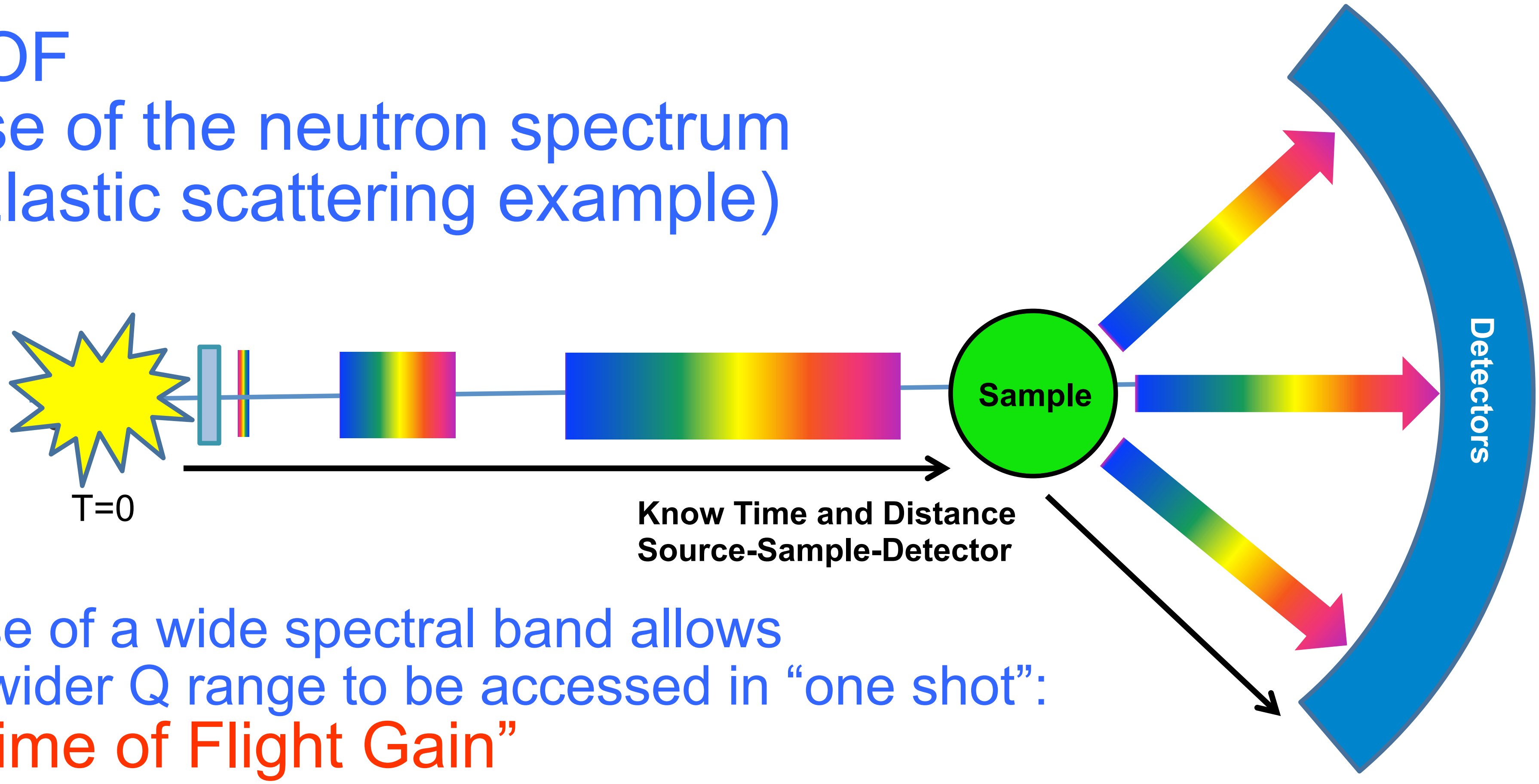
TOF use of the neutron spectrum (Elastic scattering example)

EQ-SANS Spallation Neutron Source



uses a wide spectral band

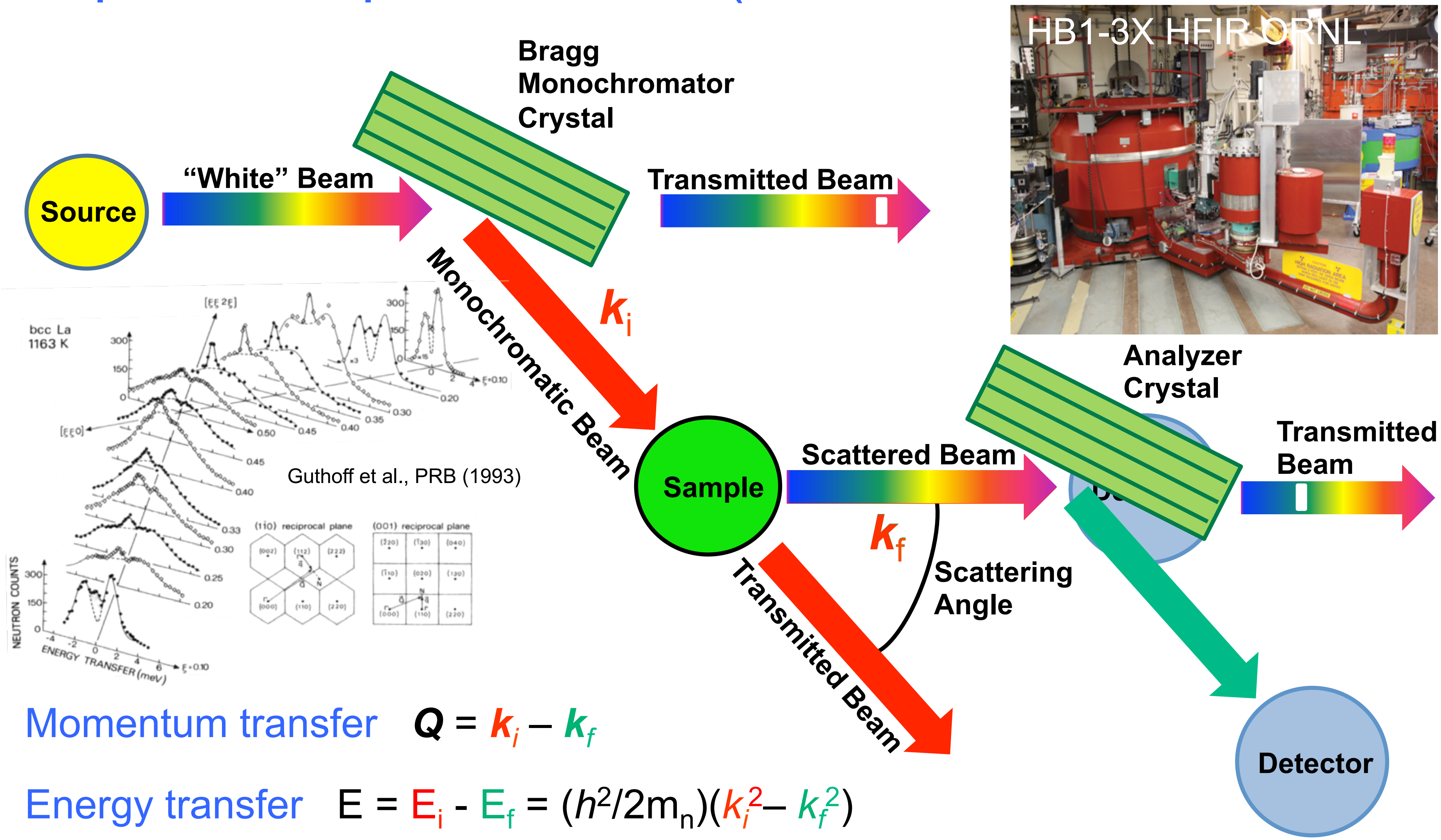
TOF
use of the neutron spectrum
(Elastic scattering example)



Use of a wide spectral band allows
a wider Q range to be accessed in "one shot":
"Time of Flight Gain"
which often makes up for that lower integrated flux
in generally wider "survey" of Q (and E for inelastic)

Caveats:
"Frame overlap" – fast neutrons from later pulses catch slower ones from this
solutions: frame choppers (usually a system thereof)
and/or some long λ reflection filtering
- often also need to shield from unmoderated fast neutron and
gamma flash of those succeeding pulses ("T-zero")

Inelastic: Classic Inelastic Reactor Instrument "Triple Axis Spectrometer" (Brockhouse 1955 …)

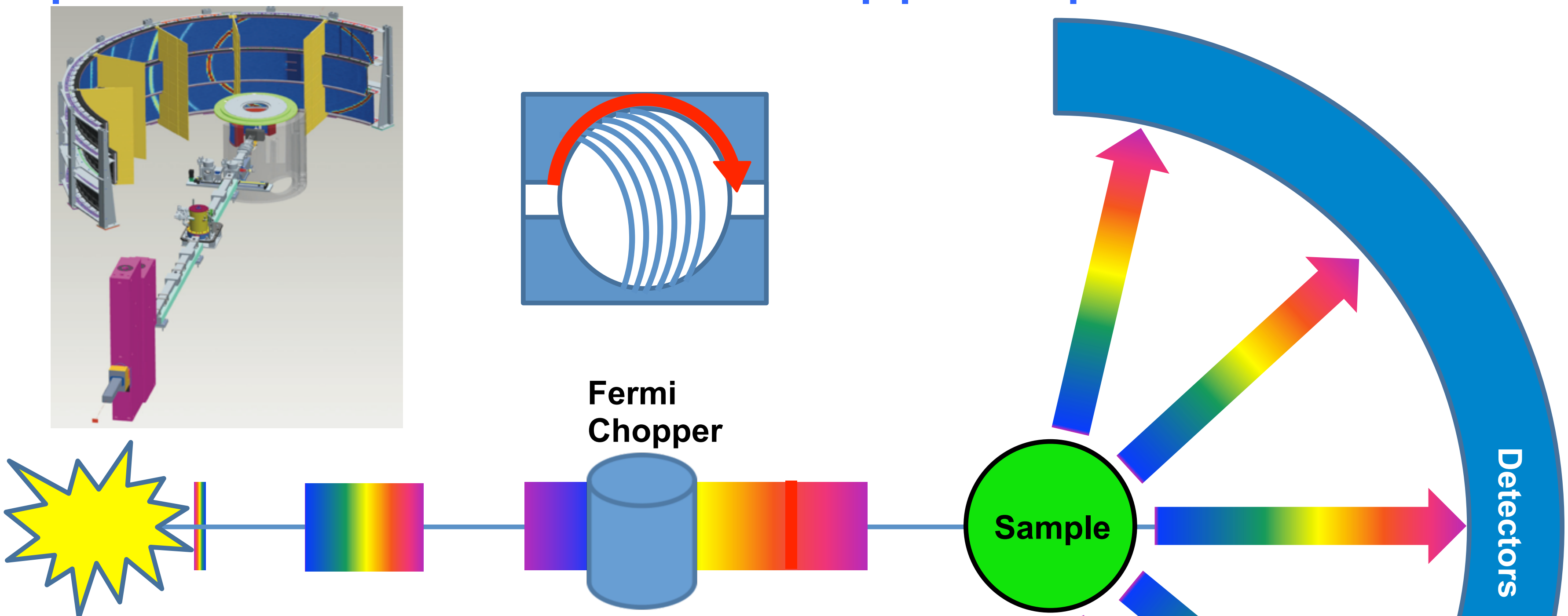


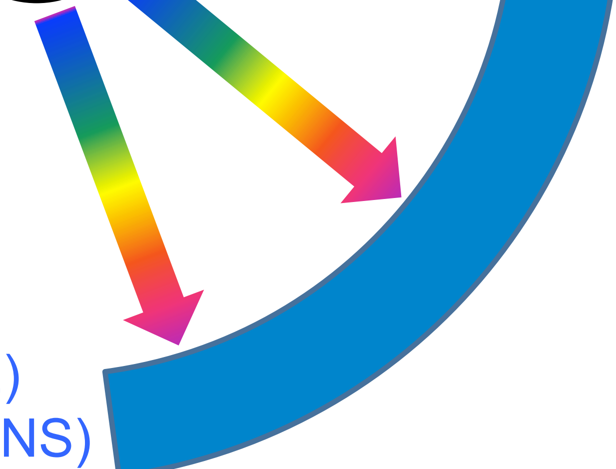
Momentum transfer $\boldsymbol{Q} = \boldsymbol{k}_i - \boldsymbol{k}_f$

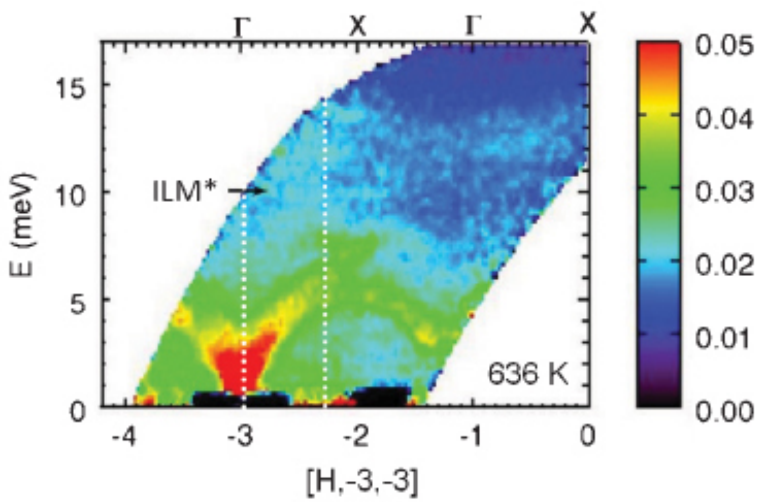
Energy transfer $E = E_i - E_f = (h^2/2m_n)(k_i^2 - k_f^2)$

Looks at a spot in (Q,E) – but you can scan closely where you want …

Inelastic example:
Simplified Pulsed Source Chopper Spectrometer







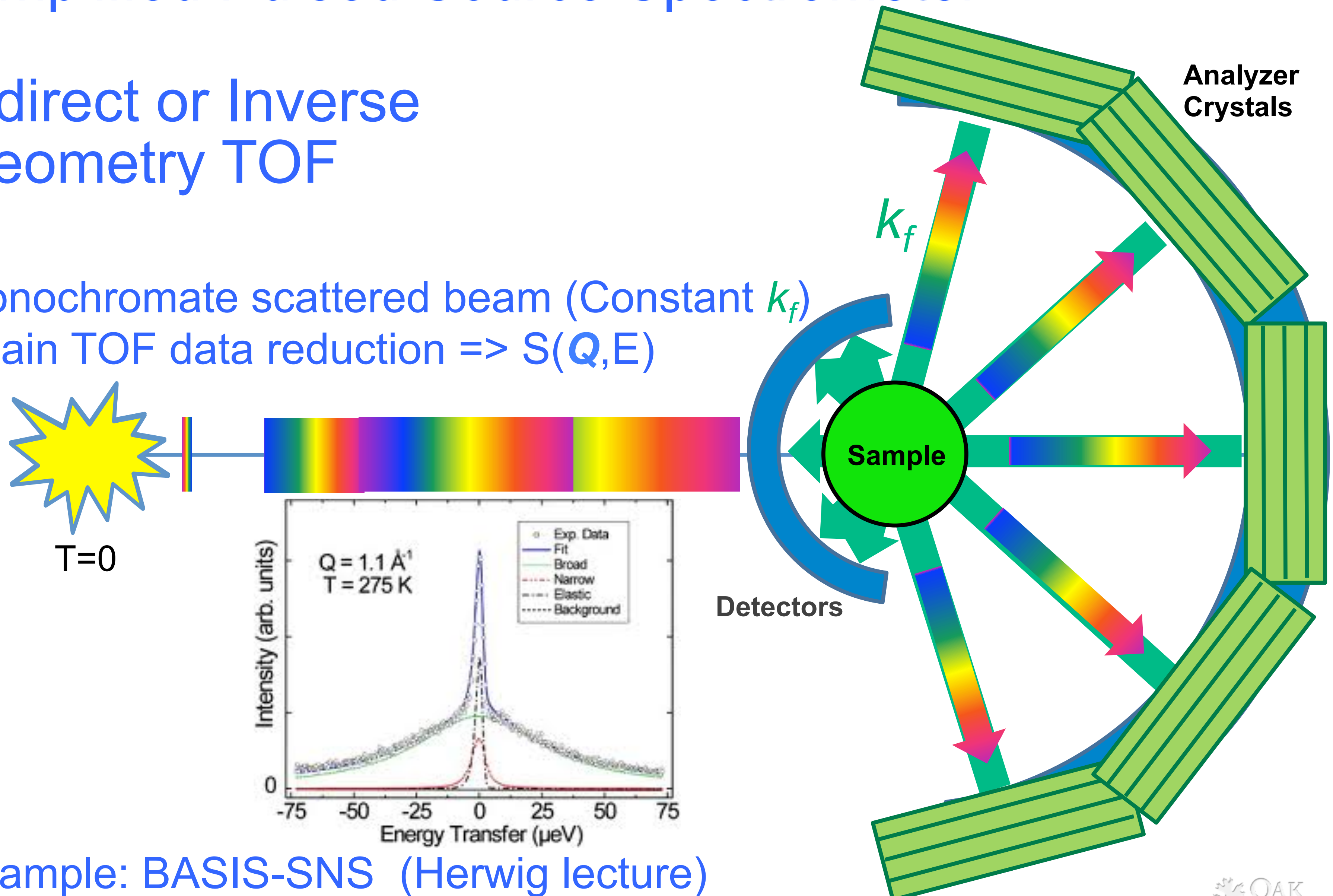
Monochromate incident beam (Constant k_i)

TOF data reduction
Wide swath of (**Q**,E)
(data from ARCS-SNS)

Inelastic example:
Simplified Pulsed Source Spectrometer

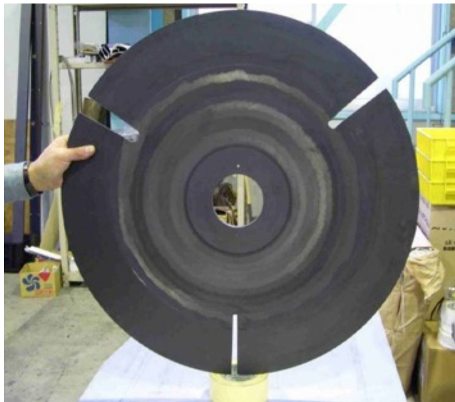
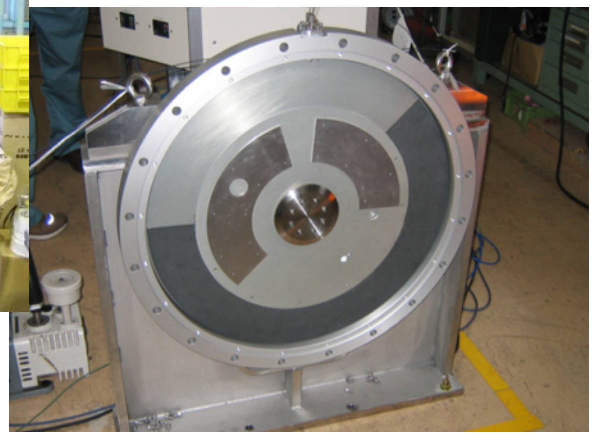
Indirect or Inverse Geometry TOF

Monochromate scattered beam (Constant k_f)
Again TOF data reduction => S(***Q***,E)



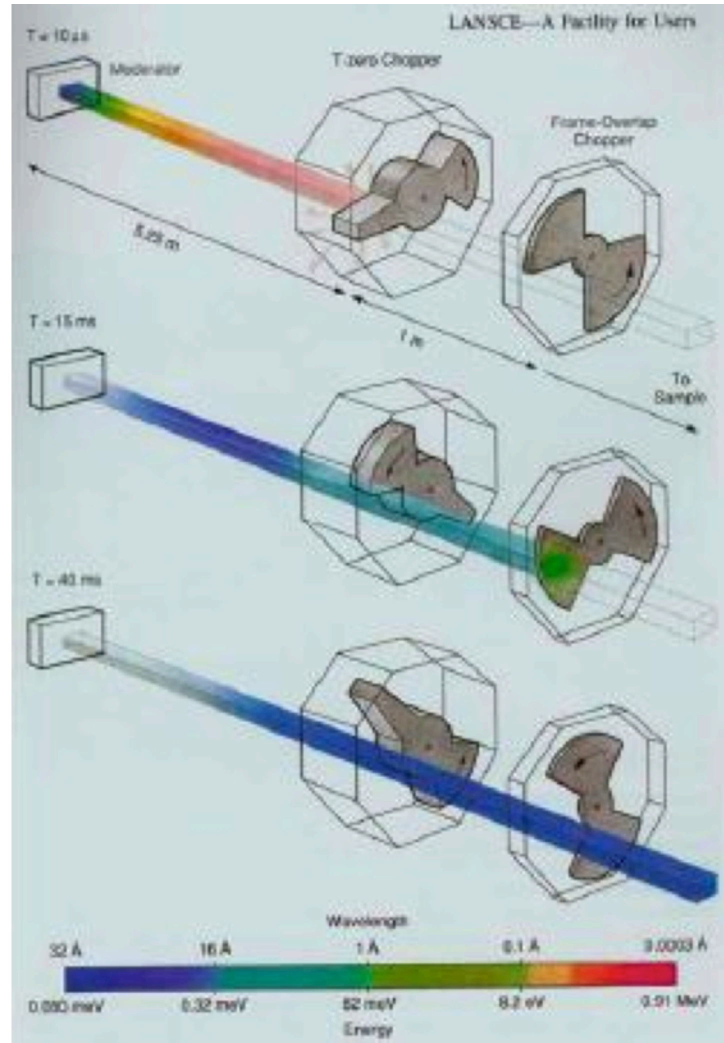
Example: BASIS-SNS (Herwig lecture)

Other Choppers: pulse selection, frame & "T-zero"

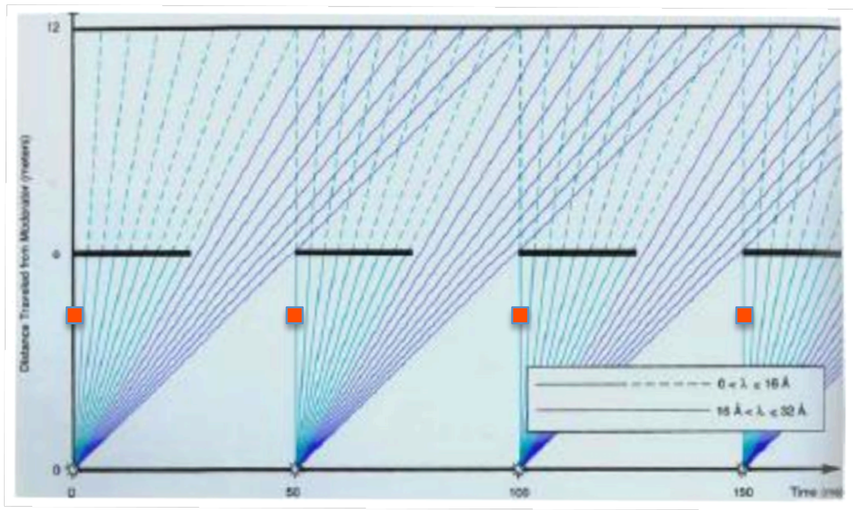
Pulse and frame disc choppers - J-PARC

T-zero choppers – Rotating heavy metal to supresss γ and fast neutron "flash" when accelerator proton beam hits spallation target



(Very Simple) TOF Path-Timing Diagram

Distance from source



Path-time graph for butterfly frame chopper choosing second frame (16-32Å) frame SPEAR reflectometer (12.38m, 20Hz)

- LANSCE Spallation Source, Los Alamos

High pressure gas detectors

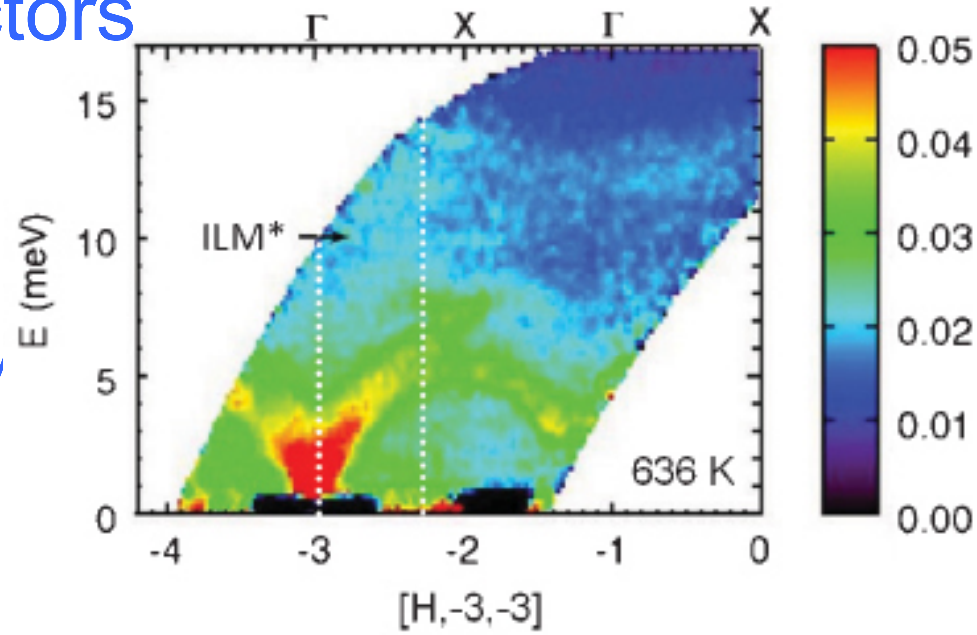
~75% of detectors for neutron scatterin use ^3He at ~3-20 atm (with something easier to ionize added).

“Proportional counter”: energetic particles from n reaction ionize gas, HV (few kV) cascades e charge signal to anode.

Usually cylindrical: collecting at V at both ends of anode gives position sensitivity, limit resolution ~few mm (charge track cloud size).

These detectors are efficient (usually ~90%+), stable, low noise, and have excellent gamma discrimination, and good timing (~μs) … but they may soon become a thing of the past.

BF_3 (Shull and Wollan used it) or $^{10}BF_3$, timing and resolution problems ...

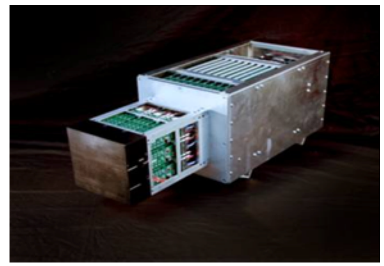


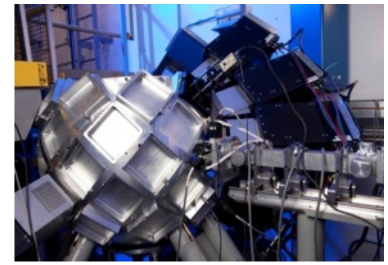
Neutron scintillator detectors – 1

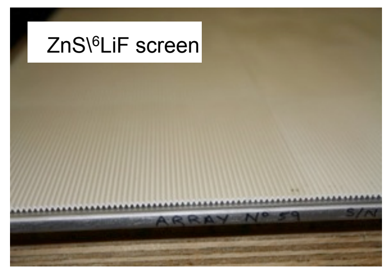
Typically light is collected from a ^{6}Li doped phosphor screens: ZnS (opaque) or GS20 (clear)

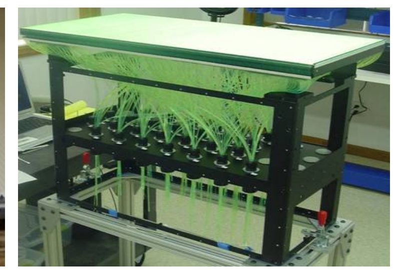
Can use traditional nuclear, HEP coincidence analysis technique: analysis of photomultiplier tube array signals (Anger Camera) 1mm x 1mm resolution & very fast. PM tubes gamma “sensitive”. Installed TOPAZ single xtal.

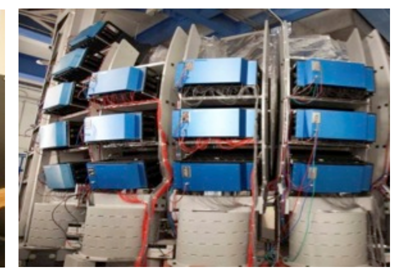
New technique on two SNS diffraction machines (POWGEN, VULCAN) crossed layers of light shifting optical fibres which collect ZnS blue light convert to green to carry to optical detectors. Resolution ~5mm x 60mm & fast. Efficiencies ~50-60%. Gamma rejection of screens deemed “fair” …







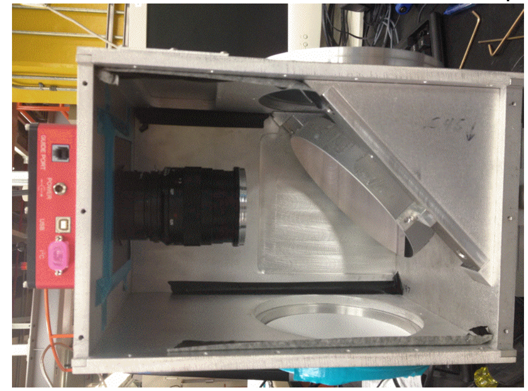




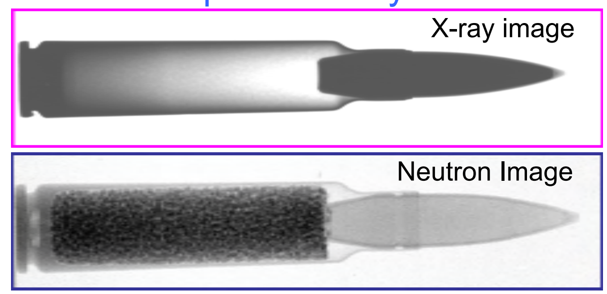
Neutron scintillator detectors – 2

Neutron Radiography & Imaging: CCD Camera views a phosphor screen – again usually $^{6}Li/ZnS$. Sub mm resolution, but CCD/high-speed video readout is slower than neutron TOF requires. Gamma sensitive (at right the camera views the ZnS screen through right angle mirror reflection), sensitivity is fairly low, linearity is a problem (cameras are developed to human sensitivity which is logarithmic). Tradeoff between resolution, efficiency, γ background and optics.

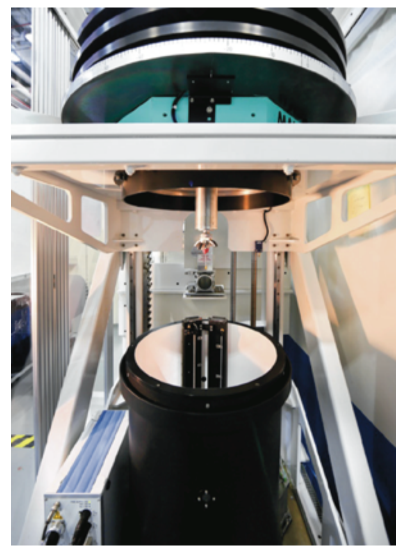
M. Fleenor ORNL
N Instrument Group

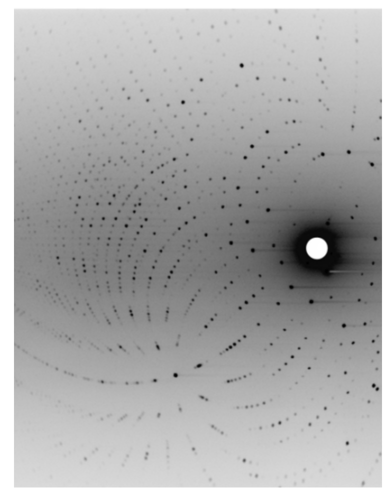


N vs X complementarity:



High resolution imaging and very high resolution diffraction: $BaFBr:Eu^{2+}$ "storage phosphor" material for radiation imaging either doped with Gd_2O_3 or a ^{6}Li or ^{10}B salt. Great resolution (<100μm), <u>very</u> slow readout (by laser scan: Photon Stimulated Luminescence). Dynamic range? And once again γ sensitivity is a problem.





IMAGINE - HFIR
Protein Xtal

Neutron shielding & beam shaping

For a good shielding, aperture, chopper, selector material we seek high cross section neutron nuclear reactions producing something more stoppable or less n detectorable: i.e. softer photons (weak γ or x-ray=>Pb, steel, concrete) or charged particles (best)

Some that have been used:

$n + {}^{3}He \rightarrow ({}^{4}He)^{*} \rightarrow {}^{1}H + {}^{3}H$, Q=0.77MeV (${}^{3}He \sim 1.4 \times 10^{-4}\%$) $\sigma_a = 5.33kb$

$n + {}^{6}Li \rightarrow ({}^{7}Li)^{*} \rightarrow {}^{4}He + {}^{3}H$, Q = 4.8 MeV (${}^{6}Li \sim 7.5\%$) $\sigma_a = 0.94kb$

$n + {}^{10}B \rightarrow ({}^{11}B)^{*} \rightarrow ({}^{7}Li)^{*} + {}^{4}He$, Q = 2.3 MeV 0.5MeV γ, 94% branch
$\rightarrow$ 7Li + 4He, Q = 2.8 MeV, 6% branch (${}^{10}B \sim 20\%$) $\sigma_a = 3.84kb$

$n + {}^{113}Cd \rightarrow ({}^{114}Cd)^{*} \rightarrow {}^{114}Cd + \gamma$, Q~8MeV (${}^{113}Cd \sim 12\%$) $\sigma_a = 21kb$

$n + {}^{157}Gd \rightarrow ({}^{158}Gd)^{*} \rightarrow {}^{158}Gd + \gamma$, Q~8MeV (${}^{157}Gd \sim 16\%$) $\sigma_a = 255kb$

$n + {}^{235}U \rightarrow ({}^{236}U)^{*} \rightarrow$ (fission fragments), Q~200 MeV (${}^{235}U \sim 0.7\%$) $\sigma_a = 0.68kb$

Cross sections better for slower/colder neutrons
So mixing in moderator can help, e.g. ^{6}Li-poly, ^{10}B-poly, Borax $\sigma_a \sim 1/v \sim \lambda \sim 1/\sqrt{T}$

Also useful: sandwiching of "better" (high σ_a low γ but expensive) in front of "worse" (lower σ_a higher γ but cheap or structurally convenient) – i.e. 6Li-poly//B-Al//Cd

Incident beam monitoring

When absolute scattering power matters (SANS, NReflectivity …) or relative normalization between scans does (i.e. nearly always)

⇒ Low efficiency (<0.1%) transmission detectors in pre-sample path*

$n + {}^{3}He \rightarrow ({}^{4}He)^{*} \rightarrow {}^{3}H + {}^{1}H$, Q=0.77MeV (${}^{3}He$~$1.4\times10^{-4}$%) σ_a= 5.33kb

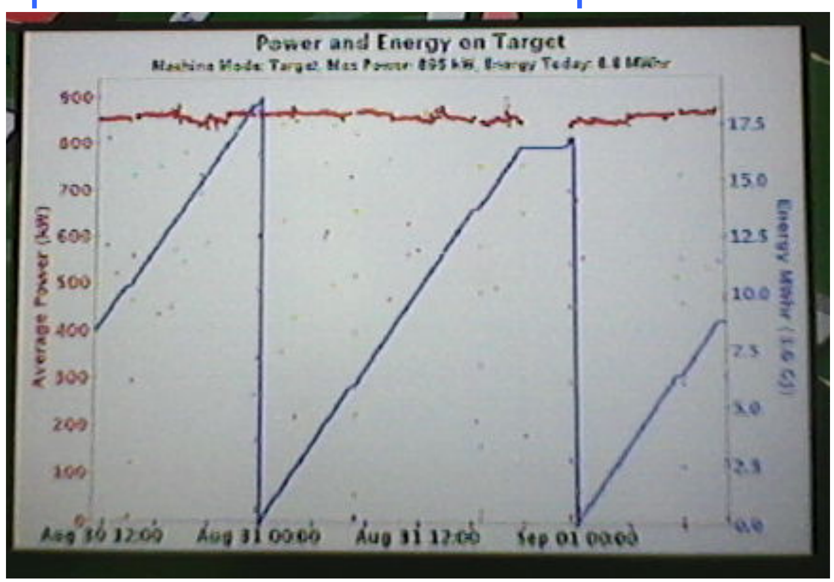
$n + {}^{14}N \rightarrow ({}^{15}N)^{*} \rightarrow {}^{14}C + {}^{1}H$, Q = 0.63 MeV (${}^{14}N$~99.6%) σ_a= 1.9 b

(so can just use normal He or N_2 in a gas detector …)

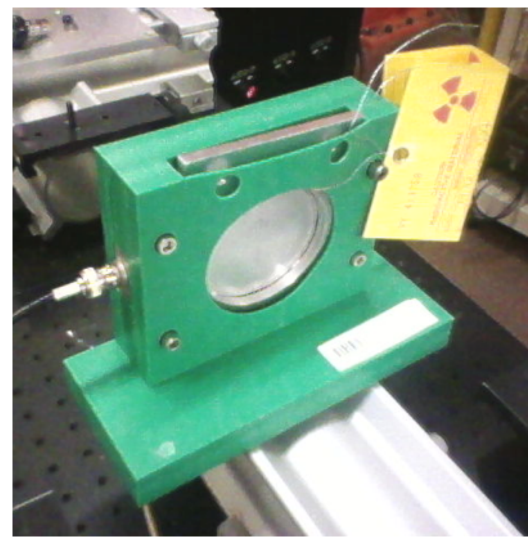
$n + {}^{235}U \rightarrow ({}^{236}U)^{*} \rightarrow$ (fission fragments), Q~200 MeV (${}^{235}U$~0.7%) σ_a= 0.68kb

He monitor ORDELA Inc.

Reactor power stable ~%, but n flux rises as fuel burns. Accelerator operation is somewhat spottier:



SNS P&E vs t



Fission monitor

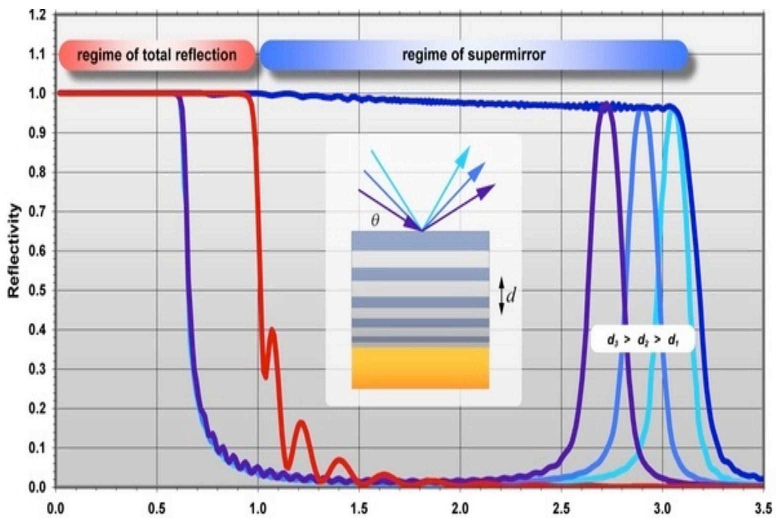
* γ insensitivity a must here

Neutron transport

The penetrating power of neutrons can make this relatively easy. Thermal neutrons can go a long way in dry air (<10% loss/m for 4Å neutrons). Long flight paths and “get lost” tubes for transmitted beams do require vacuum.

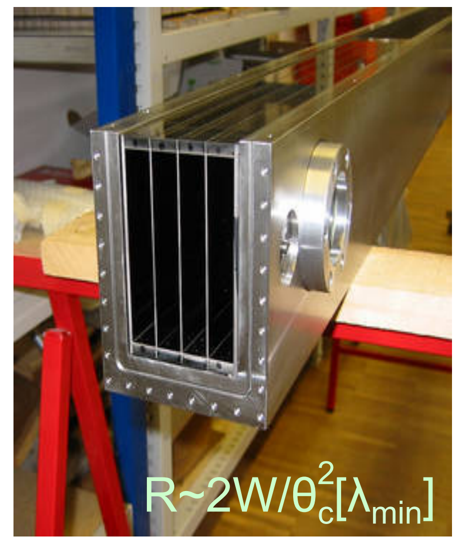
Windows: Aluminium, Quartz, Sapphire & Silicon all have good thermal neutron transmission. Single crystals of the last three can be used to avoid losses due to Bragg scattering. Diamond is also good, and soon affordable?

To transport neutrons a long way from the source (to lower background or just get space) we can use total external reflection in evacuated “neutron guides”:



Convention for guide mirror angles
m=0.1 deg/Å angle, i.e. relative to θ_c Ni

Guide Installation at ISIS UK

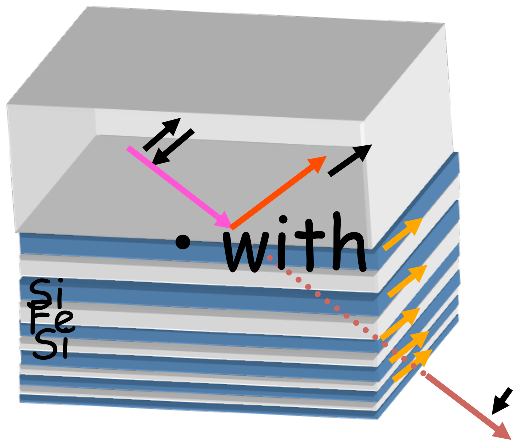


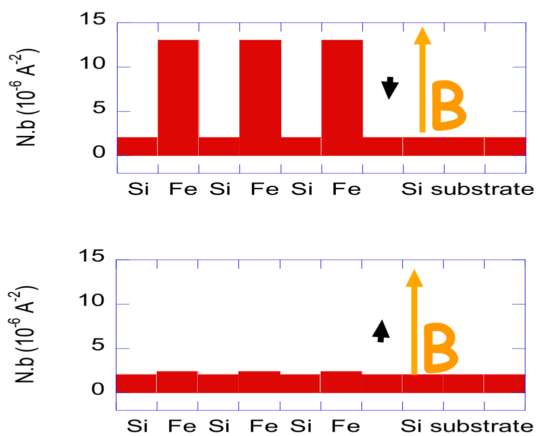
Multichannel **Curved** Guide
Fabricated by Swiss Neutronics

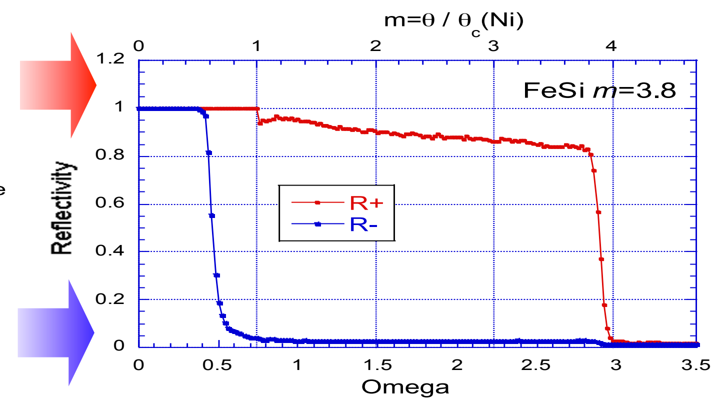
Selecting/Analyzing & Manipulating Neutron Spin

Polarized neutrons, mirrors, interface **reflectivity** … (Majkrak and Gaulin)

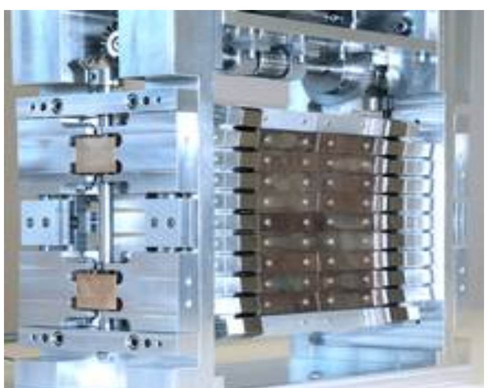
Neutron spin polarizing Supermirrors:





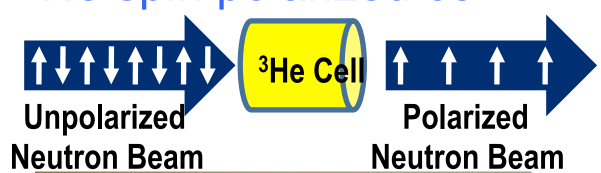


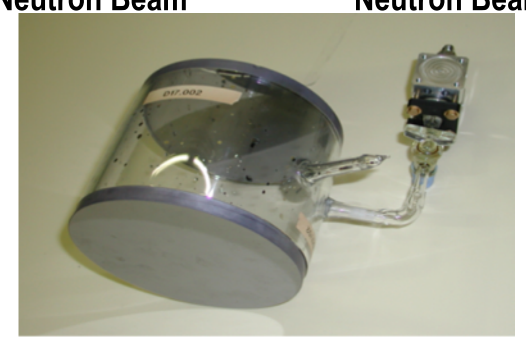
Polarizing Bragg reflection



Heusler $AlCu_2Mn$ xtal
in B field yoke

^{3}He spin polarized cell

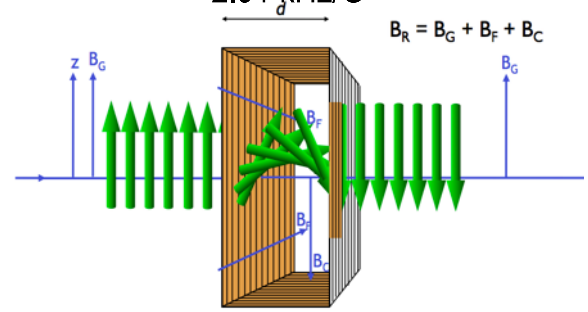




Xtal Si windowed 3He cell (D17 – ILL)

Mezei type Flipper

Non-adiabatic 90° B change
Neutron Larmor precession
2.91 kHz/G



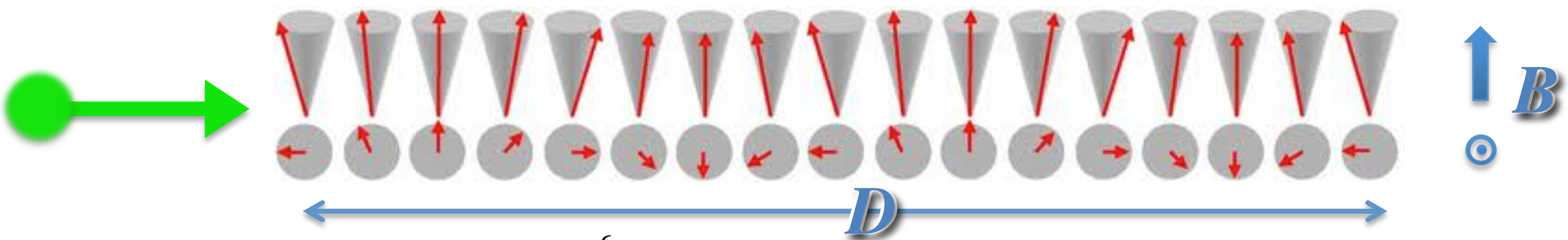
17 G-cm will "π-flip" a 4Å neutron passing through the coil

Neutron Spin Optics

A neutron's magnetic moment and (antiparallel) intrinsic angular momentum undergoes precession around the perpendicular component of an applied magnetic field and will be guided by the parallel component … (some quantum caveats apply)

$$\frac{d\vec{s}}{dt} = \gamma_n\left(\vec{s} \times \vec{B}\right) \qquad \gamma_n = \frac{\mu_n}{\hbar/2} = -1.83\times10^{8}\ radian/s/T = -2.91kHz/G$$

n Gyromagnetic ratio



Phase: $$\Delta\phi = \gamma_n B_\perp t = \gamma_n B_\perp\left(\frac{D}{\mathrm{v}_n}\right) = \begin{cases} \gamma_n B_\perp\left(\dfrac{D}{p/m_n}\right) = \gamma_n B_\perp\left(\dfrac{D}{(h/\lambda)/m_n}\right) = \dfrac{m_n\gamma_n}{h}B_\perp D\lambda & \propto \lambda \\ \gamma_n B_\perp\left(\dfrac{D}{\sqrt{E/2m_n}}\right) = \sqrt{2m_n}\gamma_n\dfrac{B_\perp D}{\sqrt{E}} & \propto \dfrac{1}{\sqrt{E}} \end{cases}$$

Precession of polarization is a 3rd way to determine neutron wavelengths and/or energies

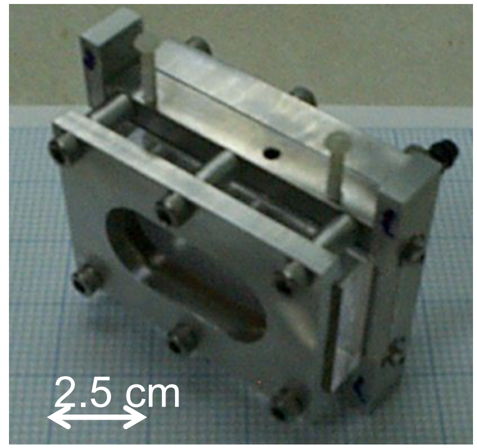
Can be used as a phase "clock" and in very carefully controlled magnetic field conditions this can be used in studies of soft matter dynamics to resolve very small energy changes (meV…neV) – akin to NMR and DLS. This is **Neutron Spin Echo.**

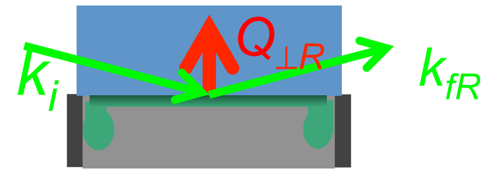
More recently these techniques have been adapted to resolve very small angular deviations in the ultra-small angle scattering range (SESANS) and not quite specular reflection (SE Grazing Incidence SANS – SERGIS)

Sample environment – general considerations

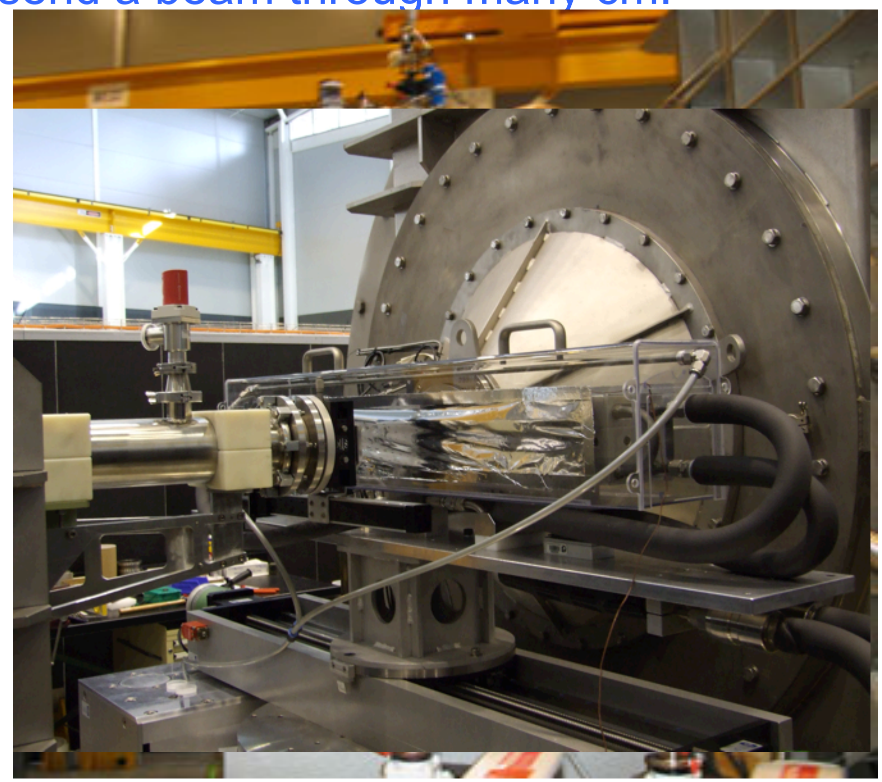
Again the penetrating power of neutrons can make this relatively easy.

Windows and sample environment enclosures: Aluminium, Quartz, Sapphire & Silicon all have good thermal neutron transmission. Single crystals of the last three can be used to avoid losses due to Bragg scattering – if necessary you can send a beam through many cm.





Reflection geometry cell for NR and SANS studies of adsorbed layers and colloidal solution morphology near surfaces. Incident and scattered beams pass through 8cm of crystal quartz slab. Transmission at 4Å ~75%

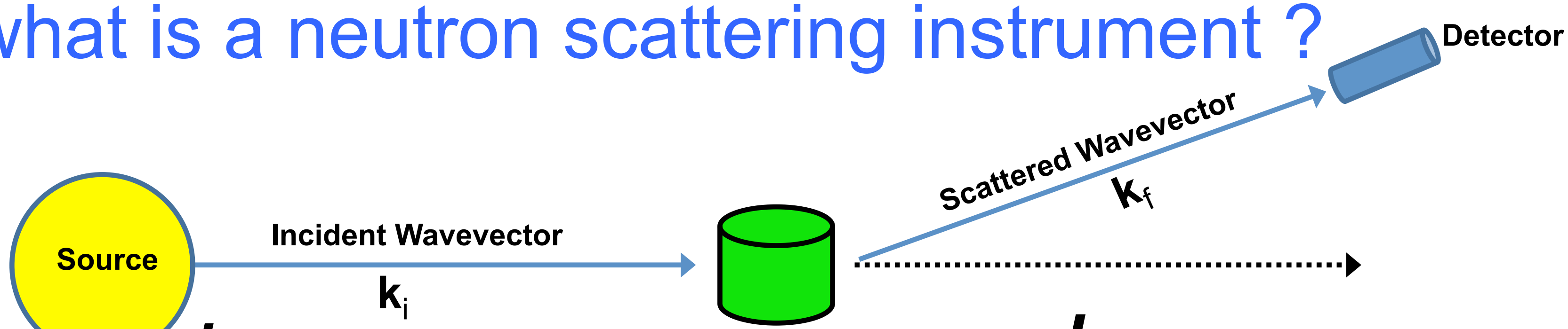


Weak scattering power and relatively poor detector resolution means that means instruments tend to be large and have a largish sample position that does not have to be in vacuum. The typical sample area on a modern SANS machine (30m+) allows for about 1m or so of sample environment beam path. Large installations and ancillary access possible.

Quokka SANS sample position – In-situ SANS Rheometer / 11T Horizontal field magnet
- OPAL ANSTO

Oak Ridge National Laboratory

So, what is a neutron scattering instrument ?



k_i

Wavelength range
- moderator
  ambient, cold, hot

Monochromatic
"white" – moderated
"pink" – filtered moderator

Pulsed
– wavelength frame ?

Polarized ?

Sample

Alignment matters:
- Single xtal, flat interface

Or doesn't:
Powder, amorphous solid, liquid, solution, gas

Length (k) or energy (E) scale of interest ?

Scattering power & transmission

Sample environment:
T, P, B, …

Phase changes: scale, rate, reversibility …

k_f

Structure, kinematics or dynamics … ?

Single wavelength or range ?
Linear or area detector ?

Resolve or filter its energy?
- Xtal or TOF chopper?
- Elastic, quasi-elastic or inelastic. Range?

High resolution, low resolution, counting time ?
⇔ Sample size, stability, scattering power

Analyze final polarization?

Elastic Neutron Scattering Instruments

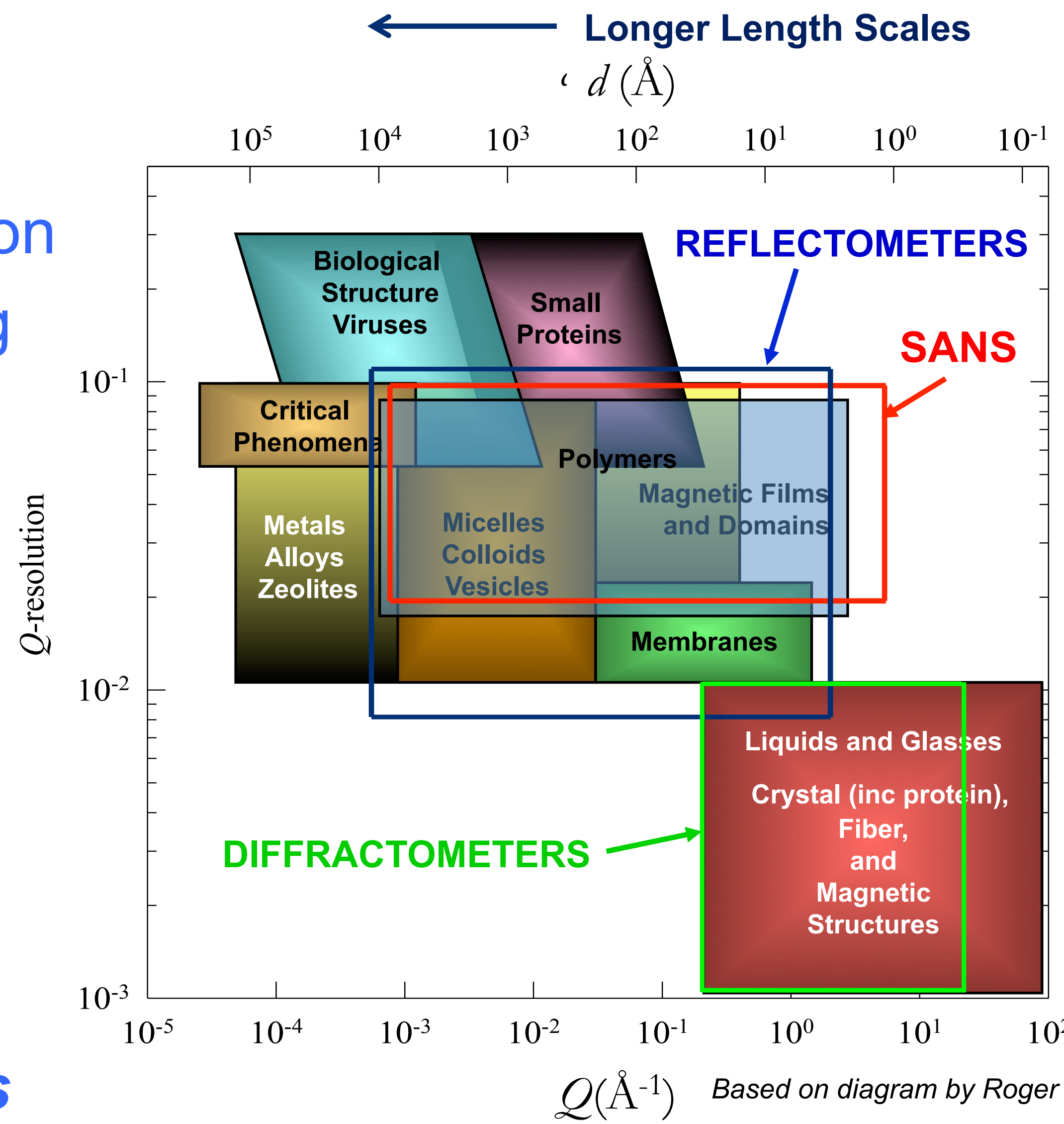
Techniques:

- Powder diffraction
- Single Crystal diffraction
- Small Angle Scattering
- Reflectometry

To determine the average structure of materials.

How the atoms are arranged or are rearranging.

Structure & Kinematics



Based on diagram by Roger Pynn

Inelastic Neutron Scattering Instruments

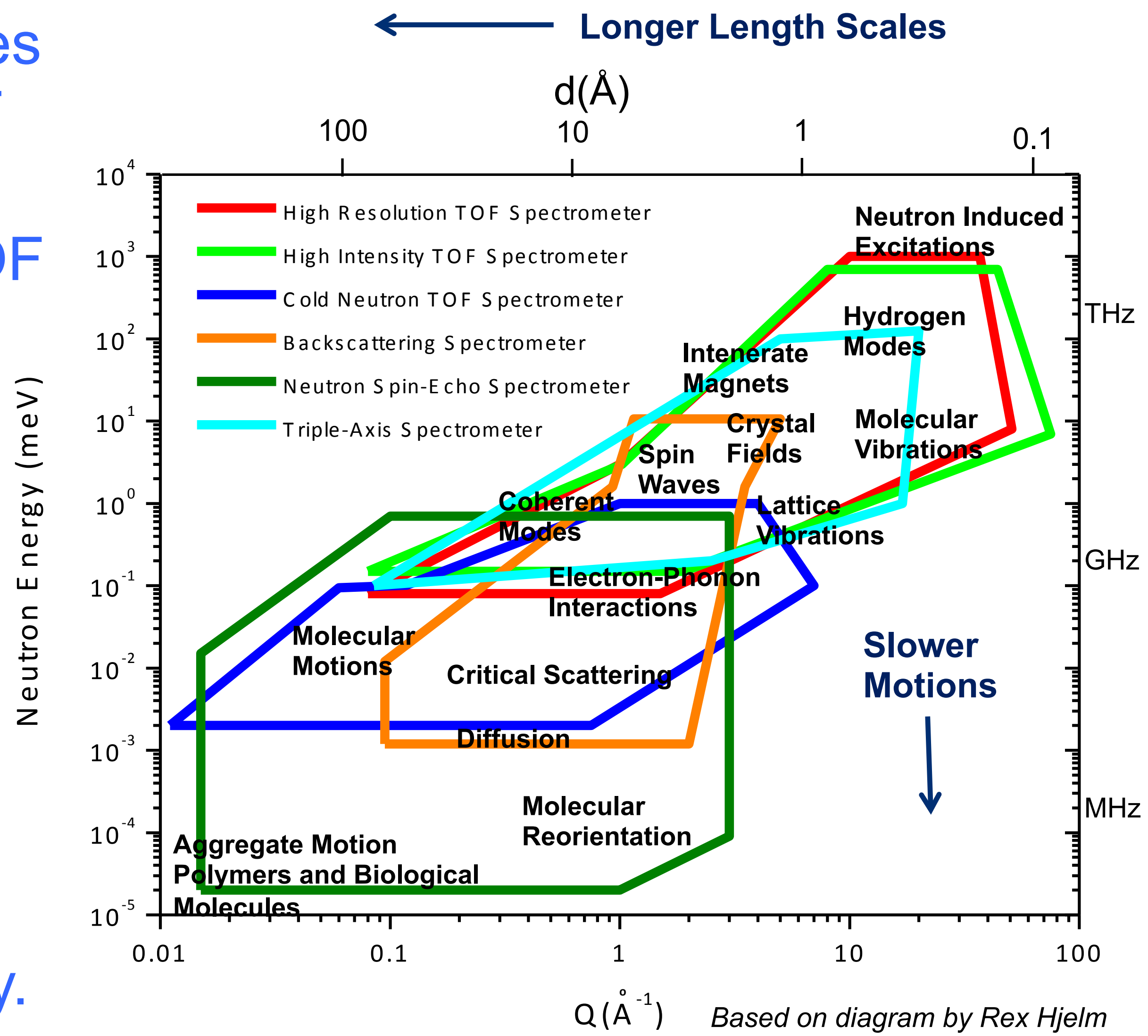
Spectrometry Techniques

- Direct Geometry TOF
- Triple-Axis
- Indirect Geometry TOF
  - Backscattering …
- Neutron Spin-Echo

Atomic, molecular or assemblage dynamics: phonons, magnons, diffusion …

How are the atoms are moving within a given structure or morphology.

Dynamics



Based on diagram by Rex Hjelm

Note: Big facilities, long user lead times …

What 1 or 2 billion $ buys in terms of neutron sources:

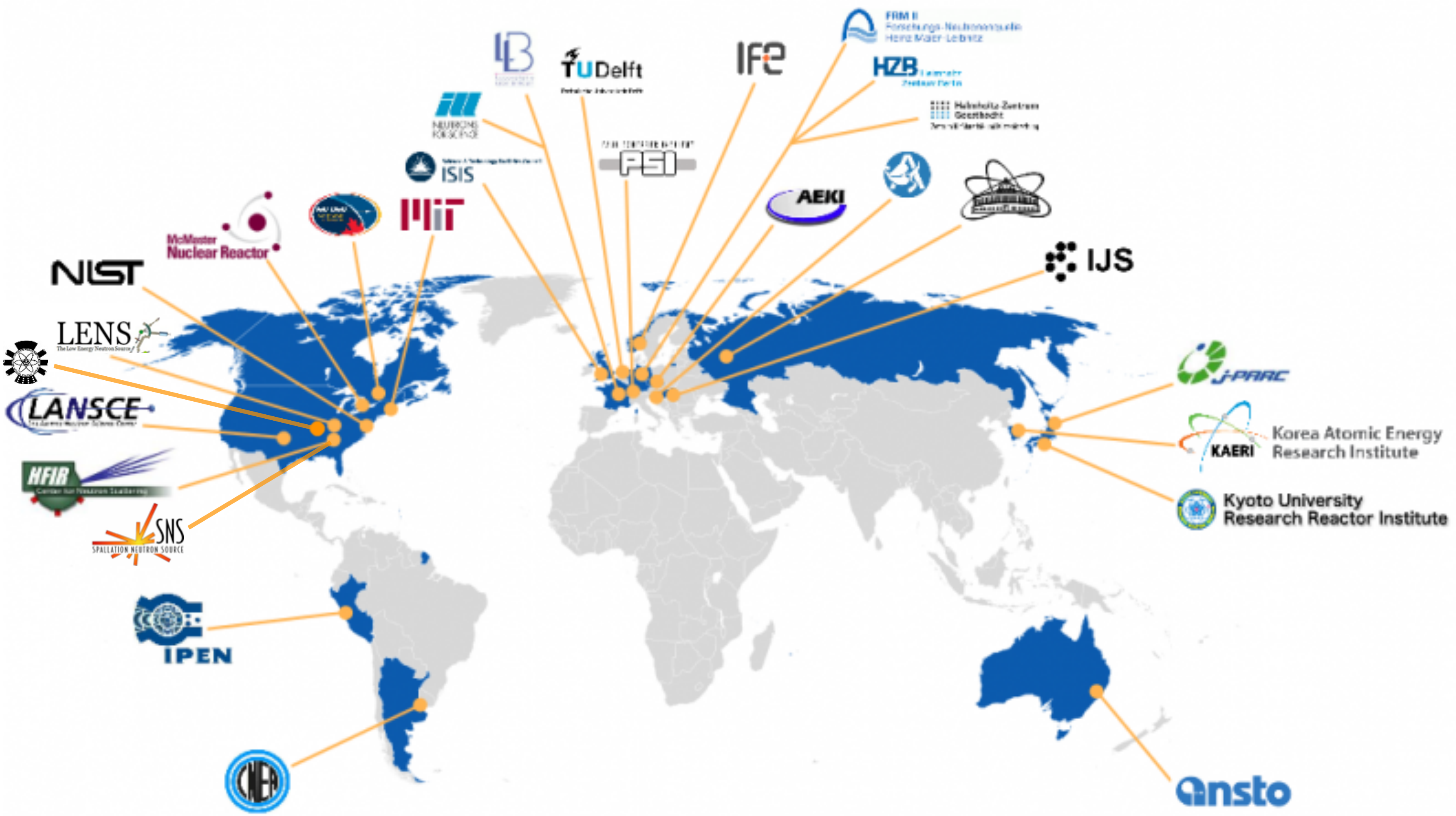
HFIR – ORNL

SNS - ORNL

In pure flux terms neither compares very well with a the photon brightness of a bench top x-ray source. (Let alone a rotating anode or synchrotron) & neutron interactions tend to be fairly weak …

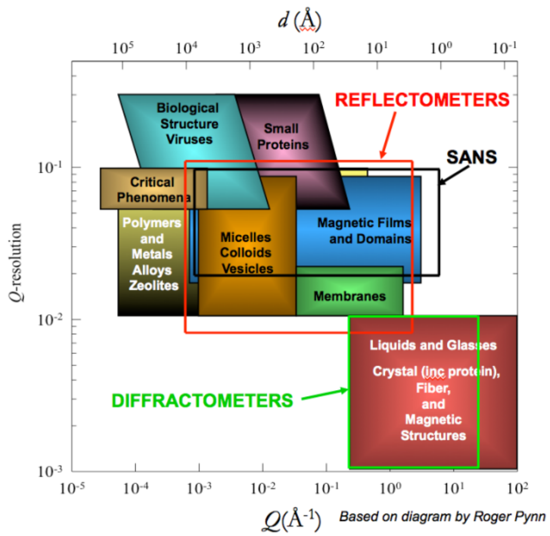
Where can I do neutron scattering ?

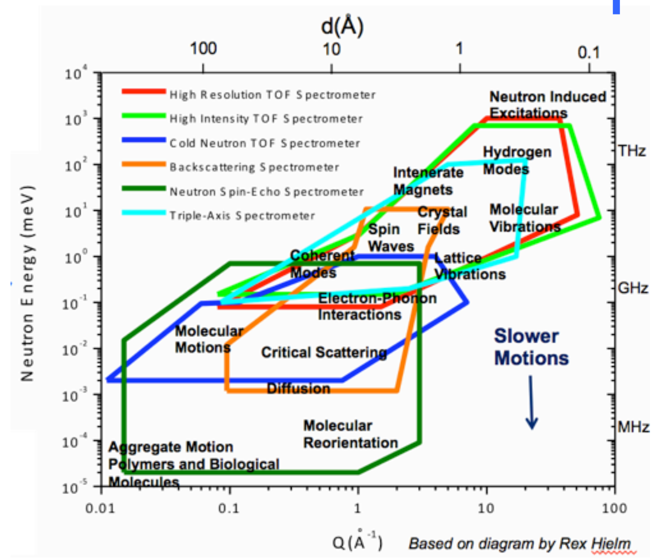
Major scientific neutron scattering sources worldwide



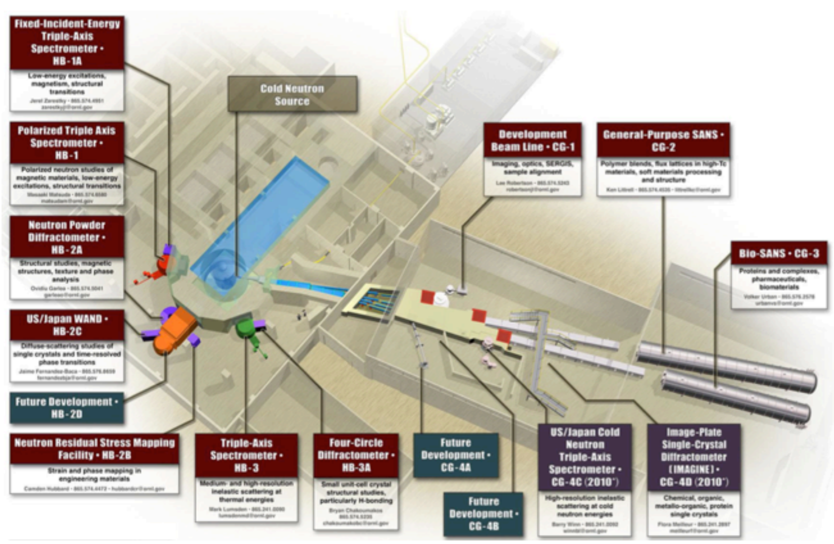
Adapted from www.veqter.co.uk website

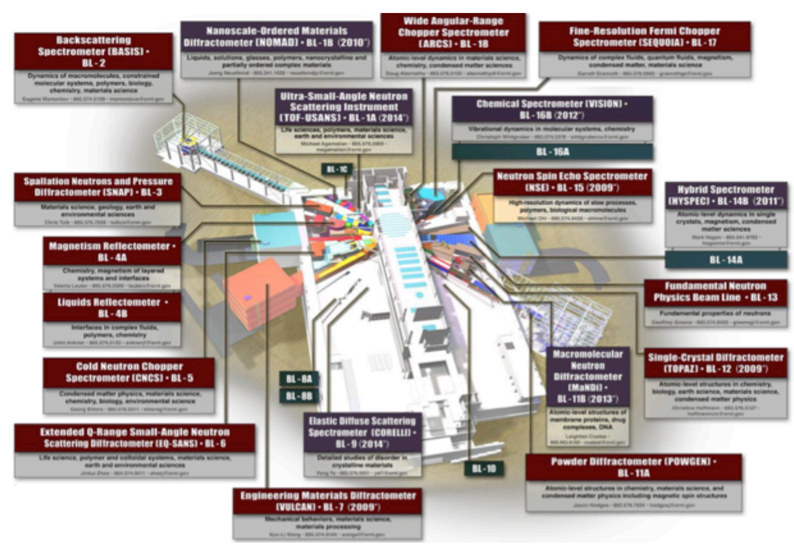
The neutron zoo in information and real space





Covers 7-8 orders of magnitude in length and energy (time), 2-3/instrument





HFIR and SNS instruments.

Similar extensive suites at NCNR-NIST, ILL (France), ISIS (UK), LANSCE-LANL, …

Conclusion: Why neutrons ?

" … because [neutron scattering] provides information about the structure of materials that cannot be obtained in simpler, less expensive ways."

1. Neutrons have the right wavelength
2. Neutrons see the Nuclei
3. Neutrons see light Atoms next to Heavy Ones
4. Neutrons measure the Velocity of Atoms
5. Neutrons penetrate deep into Matter
6. Neutrons see Elementary Magnets
7. And (because) scattering is inherently statistical

" … in spite of all these penalties of a signal-limited technique, neutron scattering continues to occupy an important place among the panoply of tools available to study materials structure because it can often provide information that cannot be [simply] obtained *in any other way*."

R. Pynn "Neutron Scattering—A Non-destructive Microscope for Seeing Inside Matter" in *Neutron Applications in Earth, Energy and Environmental Sciences*, L. Liang et al. (eds.), Neutron Scattering Applications and Techniques, Springer 2009

Acknowledgements

Material has been borrowed and adapted from presentations and publications by:

Lee Robertson, Steve Nagler, Ken Herwig, Lowell Crow, Rick Reidel, John Katsaras, Ian Anderson, Tom Mason, Mike Fleenor …

Roger Pynn, Jack Carpenter, Paul Butler, Boualem Hammouda, Bruce Gaulin, Jim Rhyne, Ross Stewart, Rob Dalgleish, Ken Andersen, Rex Hjelm …

& whoever they borrowed and adapted from (in some cases that was me).

General References:

"Elementary Scattering Theory: For X-ray and Neutron Users", D.S. Sivia, Oxford (2011)*

"Introduction to the Theory of Thermal Neutron Scattering", G.L. Squires, Cambridge (2012)

"Neutron, X-Ray and Light Scattering: Introduction to and Investigative Tool for Colloidal and Polymeric Systems" (1991)

"Neutrons, X-Rays and Light: Scattering Methods Applied to Soft Condensed Matter" (2002)
P. Lindner and T. Zemb, Elsevier North-Holland

"Neutrons in Soft Matter", T. Imae, T. Kanaya, M. Furusaka and N.Torikai, Wiley (2011)

"Dynamics of Soft Matter: Neutron Applications", Springer (2012)
V. García Sakai, C. Alba-Simionesco and S.-H. Chen

"Practical Neutron Scattering at a Steady State Source",
T. Heitmann & W. Montfrooij, Mizzou Media (2012)*

*most "accessible"

http://www.ncnr.nist.gov/summerschool/ss13/pdf/NeutronScatteringPrimer.pdf R.Pynn (1990)*

"Handbook of Neutron Optics", M. Utsoro and V.K. Ignatovich, Wiley (2010)

Neutron Scattering Source Websites

- http://neutrons.ornl.gov
- http://www.ncnr.nist.gov
- http://lansce.lanl.gov
- http://www.murr.missouri.edu/rd_material_sciences.php
- http://www.indiana.edu/~lens/

- http://www.ill.eu
- http://www.isis.stfc.ac.uk
- http://www.frm2.tum.de
- http://www.psi.ch/sinq/
- http://www.tnw.tudelft.nl/en/cooperation/facilities/reactor-instituut-delft/
- http://www-llb.cea.fr/en/
- http://www.ansto.gov.au/ResearchHub/Bragg/index.htm
- http://flnp.jinr.ru/562/
- http://www.nti.org/facilities/9/

… a more exhaustive list: http://www.neutron.anl.gov/facilities.html